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RESEARCH ARTICLE

Quantitative characterization of horizontal well production performance with multiple indicators: a case study on the Weiyuan shale gas field in the Sichuan Basin, China

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Abstract To quantitatively characterize the horizontal shale gas well productivity and identify the dominant productivity factors in the Weiyuan Shale Gas Field, Sichuan Basin, a practical productivity method involving multiple indicators was proposed to analyze the production performance of 150 horizontal wells. The normalized test production, flowback ratio, first-year initial production and estimated/expected ultimate recovery (EUR) were introduced to estimate the well productivity in different production stages. The correlation between these four indicators was determined to reveal their effects on production performance forecasts. In addition, the dominant productivity factors in the present stage were identified to provide guidance for production performance enhancement. Research indicates that favorable linear relations exist between the normalized test production, first-year initial production and EUR. The normalized test production is regarded as an important indicator to preliminarily characterize the well productivity in the initial stage. The first-year initial production is the most accurate productivity evaluation indicator after a year. The flowback ratio is a supplementary indicator that qualitatively represents the well productivity and fracturing performance. The well productivity is greatly dependent on the lateral target interval, drilling length of Longmaxi1_1^1 (LM1_1^1) and wellbore integrity. The first-year recovery degree of EUR is 24%–58% with a P50 value of 35%.

Keywords shale gas, productivity evaluation, normalized test production, first-year initial production, EUR, Longmaxi shale, Weiyuan shale gas field

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1 Introduction

Gas shale formations are organic-rich shale formations and apparently function as source rocks as well as reservoirs (Jenkins and Boyer, 2008; Beckwith, 2011; Su et al., 2007; Zou et al., 2018, 2020; Cui et al., 2019; Fang, 2019; Jin et al., 2019; Zheng et al., 2019; Zhao et al., 2020). Gas is mainly stored in the confined pore space and natural fractures of shale reservoirs in the free state or adsorbed at active surface sites of the organic matter contained within shale (Curtis, 2002). Dissolved gas can be neglected in marine shales with a high thermal maturity (Li et al., 2018a). Therefore, the adsorbed and free gas fractions comprise the total gas content and coexist in shale reservoirs, of which the adsorbed gas accounts for 20%–85% of the total gas (Curtis, 2002; Boyer et al., 2006; Hill and Nelson, 2000; Li et al., 2020). In addition to multiple gas occurrences, shale gas reservoirs are also characterized by complex and multiscale pore-fracture systems (including pore throats in shale matrices and in situ natural fractures), poor petrophysical properties with a low porosity and a nano-Darcy permeability, which cause extreme difficulties in shale gas exploitation (Javadpour et al., 2007; Wu, 2019; Zeng, 2019). Fortunately, advances in the horizontal multistage hydraulic fracture technique have provided a possibility for the economic production of shale gas from very tight shale gas reservoirs (King, 2010; Wood et al., 2011; Saldungaray et al., 2013; Wang et al., 2016).

In China, based on large-scale technical recoverable resources larger than 30 × 10^{12} m^3, shale gas has been commercially produced after resource assessment and pilot tests in the Sichuan Basin (Shandrygin, 2019; Zhao et al., 2019a). However, due to the complicated and multiple gas fluid flow regimes existing in shale matrix pore throats and natural and artificial fractures (Wang et al., 2017; Sheng et al., 2020), production performance analysis and prediction of shale gas wells encounter challenges. In particular, the dense and conductive network of fractures in the drainage volume created around shale gas wellbores leads to a high initial production and rapid production decline in horizontal shale gas wells. Therefore, new methods and data-driven analysis are necessary for shale gas well production performance analysis. In this study, 150 horizontal shale gas wells that were put into production from 2014 to 2018 in the Weiyuan shale gas field were selected to analyze and estimate their production performance. The normalized test production, flowback ratio of the fracturing fluid, first-year initial production and estimated/expected ultimate recovery (EUR) were comprehensively considered to evaluate and classify the shale gas well productivity. In addition, the main and controlling factors of the single-well productivity were analyzed and presented for further productivity enhancement.

2 Gas field overview

2.1 Hydrocarbon exploitation history

The Weiyuan shale gas field studied in this paper is geographically located within the territories of Weiyuan, Zizhong and Rong Counties of Zigong City (Fig. 1(a)). The northern part exhibits a mountainous topography, and the central and southern parts exhibit a hilly topography. Hydrocarbon exploration and development in the Weiyuan shale gas field commonly undergoes four stages, including conventional natural gas exploration and development, shale gas resource assessment, pilot testing and industrial development. The first stage of conventional natural gas exploration and development lasted from 1938 to 2006. Regional exploration in the Weiyuan shale gas field began in 1938. Since 2006, a total of 153 wells have been drilled in the Weiyuan structure, and 6 gas-bearing strata have been discovered, including the Sinian, Cambrian, Ordovician, Silurian, and Permian Maokou Formations and Triassic Jialingjiang Formation. The second stage, from 2006 to 2009, involved shale gas resource assessment. The shale gas resource potential and favorable strata and zones in this area were clarified. In the third stage, from 2009 to 2013, a pilot test of shale gas development was conducted. The first shale gas evaluation well (well 201) was drilled in the Weiyuan structure in 2009, and the corresponding target horizons were the Silurian Longmaxi Formation and Cambrian Jiulaodong Formation. Shale gas production was obtained in this well from the Qiongzhusi and Longmaxi Formations after artificial fracturing. In 2010, a 3D seismic acquisition campaign covering 104.6 km^2 was carried out in the Weiyuan shale gas field to conduct fine structural interpretation, high-quality shale reservoir prediction, sweet-spot optimization and fracture prediction. In February 2011, the first shale gas horizontal evaluation well (well Wei201-H1) was drilled, and shale gas production was achieved after fracturing. In 2012, the Changning-Weiyuan National Shale Gas Demonstration Area was approved to determine the shale gas well productivity through pilot tests. The fourth stage, from 2014 to the present, involves the industrialization of shale gas in the demonstration area. In 2014, two shale gas development programs were completed to guide shale gas development in this region.

2.2 Geological settings

Tectonically, the Weiyuan shale gas field is located in the southwestern Sichuan Basin (Fig. 1(a)) and is considered a large-scale rolling monoclinal structure with a background of paleouplift. The strata are characterized by a gentle development, small dip angle and undeveloped faults. The strata dip angle ranges from 5°–10°, and the burial depth of the Wufeng–Longmaxi Formations ranges from 1500 m to 4000 m. The Upper Ordovician Wufeng–Lower Silurian Longmaxi Formations in the Sichuan Basin and their periphery are a set of marine organic-rich shales characterized by deep-water shelf deposition, which is considered a favorable zone for shale gas accumulation (Qiu et al., 2016; Li et al., 2018b; Jiang et al., 2019a). The Longmaxi Formation with a thickness ranging from 300–600 m (Fig. 1(b)) and abundant graptolite biological fossils can be divided into two members (i.e., Longmaxi1 and Longmaxi2). Longmaxi1 primarily consists of gray-black and black shales, which can be further divided into the Longmaxi1_1 and Longmaxi1_2 submembers. Longmaxi1_1 has a thickness ranging from 36–48 m and is a set of black carbonaceous organic-rich shales with various graptolite groups and well-developed laminations. According to the lithology, sequence stratigraphy, electric properties and paleontology, Longmaxi1_1 can be further subdivided into 4 beds, including Longmaxi1_1^1 (LM1_1^1), Longmaxi1_1^2 (LM1_1^2), Longmaxi1_1^3 (LM1_1^3) and Longmaxi1_1^4 (LM1_1^4) (Fig. 1(c)).

LM1_1 is identified as the interval of interest for shale gas production in the Weiyuan shale gas field in the Sichuan Basin. Seismic interpretation has revealed a shale gas reservoir thickness ranging from 26–48 m. The organic matter within the LM1_1 submember belongs to kerogen type I, and the corresponding thermal evolution indicates the high- to overmaturity stage with a vitrinite reflectance ranging from 2.15%–2.26%. According to laboratory core test data on in situ samples retrieved from 9 exploration wells, the total organic carbon (TOC) content ranges from 1.1%–6.7% (mean: 3.1%) (Fig. 2(a)), the reservoir porosity is 3.1%–7.4% with an average value of 4.1% (Fig. 2(b)), and the logging porosity ranges from 3.5%–7.4% with an average value of 5.1%. Quartz, feldspar, calcite, dolomite, clay minerals and pyrite are the dominant mineral components, and the brittle mineral content (i.e., the total content of quartz, feldspar and carbonate minerals) is

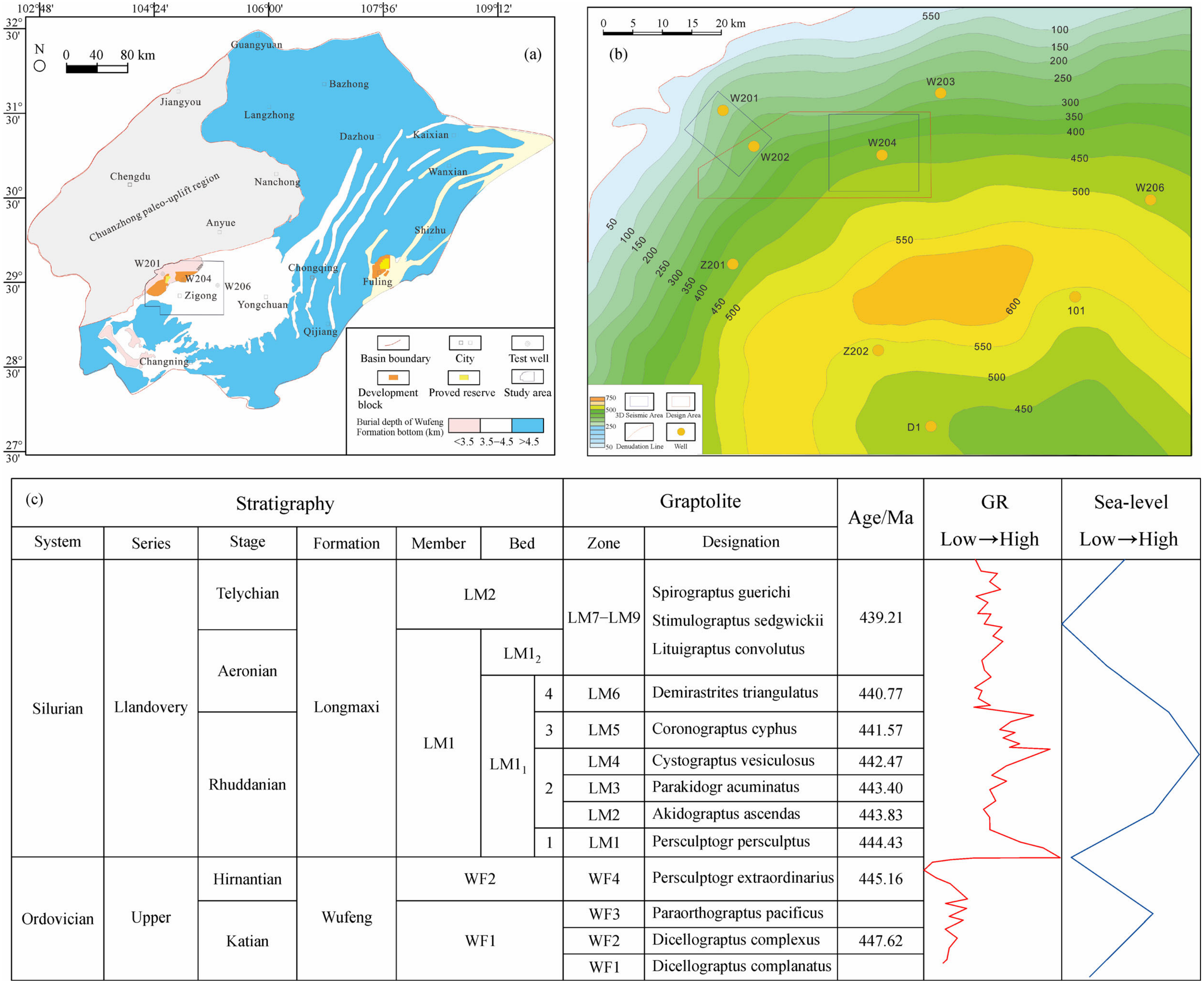

Fig. 1 (a) Location of the study area, (b) stratum thickness of the Longmaxi Formation and (c) stratigraphy of the Wufeng–Longmaxi Formations in the Weiyuan shale gas field.

59.3%–95.6% with an average value of 69.8% (Fig. 2(c)). Field test and logging interpretation has indicated a total gas content ranging from 1.3–10.2 m^3/t with a mean value of 4.4 m^3/t (Fig. 2(d)).

2.3 Production practices

After the gas field was developed in 2015, 150 horizontal wells were drilled in the shale gas reservoir and put into production in the Weiyuan shale gas field by the end of 2018. The actual vertical depth of the drilled horizontal wells ranges from 2000–3555 m, the measured depth is 4000–6000 m and the lateral length ranges from 800–2200 m (Fig. 3(a)). The average lateral length was enhanced from 1480 to 1670 m from 2014 to 2018. Multistage fracturing treatment was implemented for each well with 10–35 stages. The average stage spacing is 40–120 m, the fracturing fluid volume ranges from 11300–38800 m^3 and the proppant volume is 600–3900 tons for a single well. Both the average fracturing fluid and proppant volume intensities exhibit an increasing trend over time (Fig. 3(b)). The fracturing fluid and proppant volume intensities are the fracturing fluid and proppant volumes, respectively, per unit of lateral length, which are adopted to characterize the hydraulic fracturing scale of a shale gas well.

After wells were put into production, gas production and casing pressure were artificially restricted to reduce the reservoir stress sensitivity and maximize the single-well EUR in the initial stage. Figure 4 shows typical curves of the gas production and casing pressure of shale gas wells put into production in different years. After horizontal shale gas wells were put into production, the fracturing fluid flowed back at a high rate in the initial stage. The maximum gas production rate was reached over approximately 30 days, after which the gas production rate exhibited a relatively rapid decline in the first year. The maximum gas production rate ranged from 11×10^4–17×10^4 m^3/d, which declined to 3×10^4–4×10^4 m^3/d after 330 days. The gas production showed a slight decline after the first year, which remained at 2×10^4–3×10^4 m^3/d after 660 days and at approximately 1.0×10^4–1.5×10^4 m^3/d after 990 days. The flowing casing pressure in the initial stage ranged from 24–36 MPa, experienced a sharp decline to approximately 8 MPa after 90 days and then exhibited a slight declining trend. Typical casing pressure curves indicate a fluctuation from 90–240 days due to the running of the oil tubing to enhance fracturing fluid flowback. The flowing casing pressure also exhibited a slight decline to approximately 4 MPa after 990 days.

3 Horizontal shale gas well productivity evaluation

In addition to the complex fluid flow mechanisms and tight shale properties, large-scale reservoir stimulation has also fundamentally altered the geometry of flow in shale gas systems, requiring a new method to perform productivity evaluation and performance estimation (Wang et al., 2014;

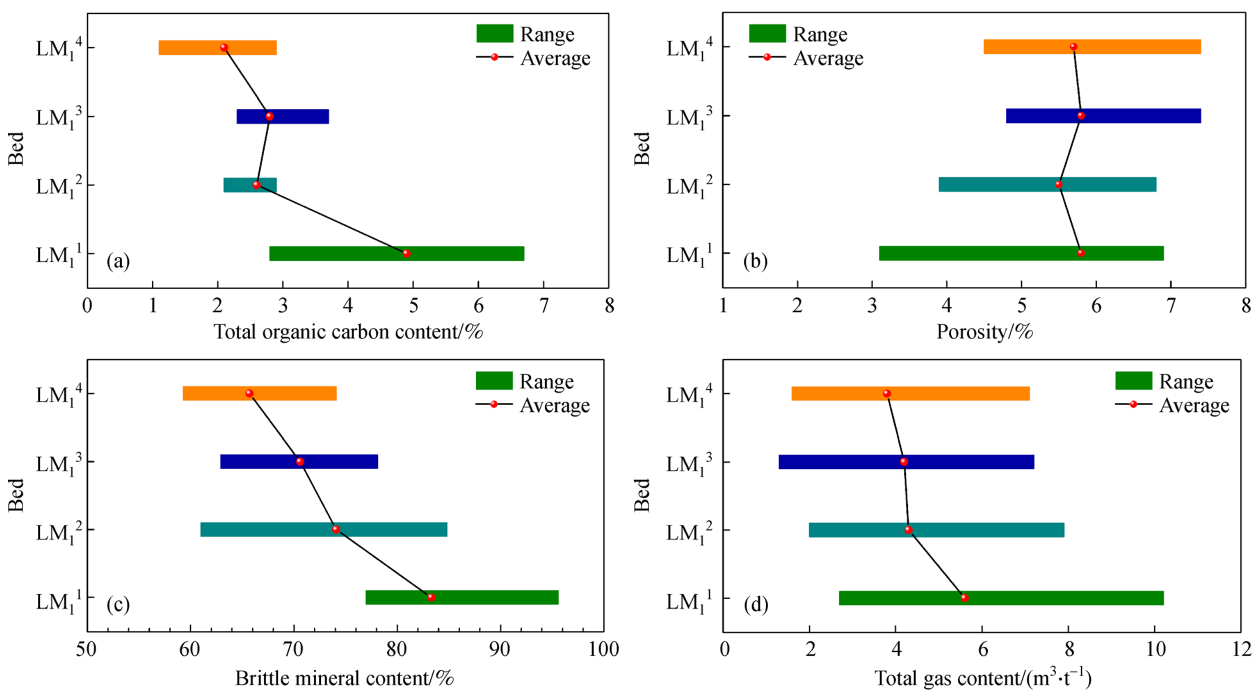

Fig. 2 Key shale gas reservoir properties in the Weiyuan shale gas field. (a) TOC; (b) porosity; (c) brittle mineral content; (d) total gas content.

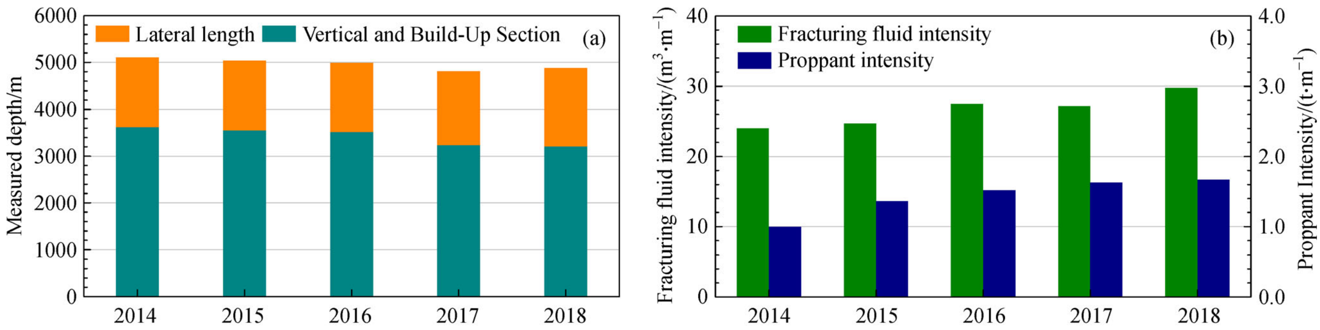

Fig. 3 Typical horizontal well depth and fracturing parameters. (a) average measured depth and lateral length; (b) average fracturing fluid and proppant volume intensities.

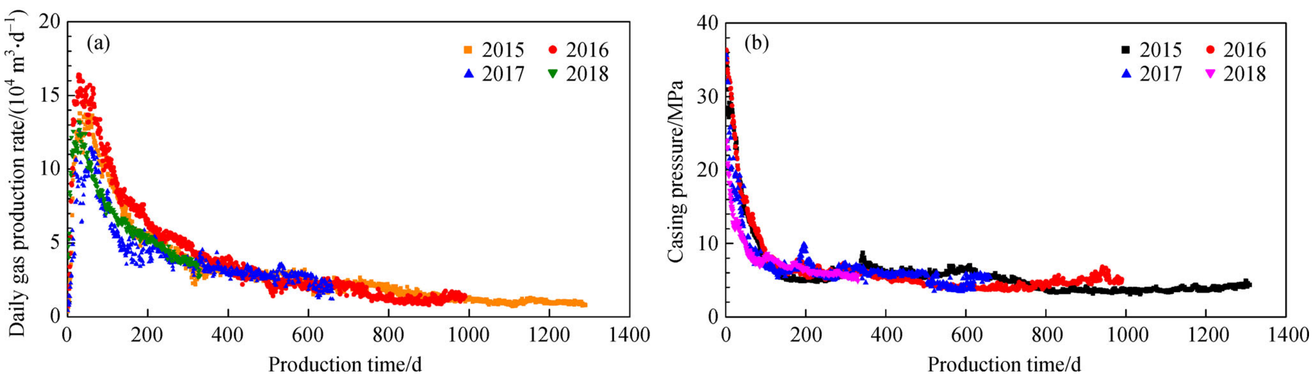

Fig. 4 Typical production curves in the Weiyuan shale gas field. (a) typical gas production curves; (b) typical casing pressure curves.

Jiang et al., 2019b). It is greatly necessary to develop a practical and reliable method to quantitatively evaluate the horizontal shale gas well productivity. In North America, the parameters of IP_{30} (initial production for 30 days) and IP_{90} (initial production for 90 days) are usually adopted as productivity indicators of shale gas wells under open-flow production conditions without surface pressure restrictions (Cipolla et al., 2009; Baihly et al., 2010; Male et al., 2016; Mirani et al., 2016). Under the constant-pressure production pattern, the initial production is a crucial indicator to quantitatively characterize the shale gas well productivity. Especially in a specific shale gas reservoir, the initial production usually exhibits a favorable linear correlation with EUR. In addition, the fracturing fluid flowback ratio is also considered a key indicator to qualitatively characterize the shale gas well productivity (Angulo Yznaga et al., 2019; Cai and Dahi Taleghani, 2019; Ibrahim et al., 2019). Although there is no clear correlation between the shale gas well productivity and fracturing fluid flowback ratio, most studies have demonstrated that a high productivity of shale gas wells often corresponds to a relatively low fracturing fluid flowback ratio. The available production performance data in the Weiyuan shale gas field also follow this understanding.

In the Weiyuan Shale Gas Field, the shale gas wellhead pressure is restricted to maintain a relatively steady production pattern to decrease fracture closure and mitigate the stress-sensitivity effect. The wellhead pressure shows a gently decreasing trend in the first year by considering conventional hydrocarbon development, which results in the limitation of shale gas well productivity evaluation based on a relatively short-term commercial production history, special pressure-restriction production pattern and experience. Therefore, a practical and reliable method to quantitatively characterize the horizontal shale gas well productivity is necessary for the design, evaluation and adjustment of development programs. In this paper, the normalized test production, fracturing fluid flowback ratio for 165 days (FBR165), initial production for 330 days (IP330) and EUR were considered to comprehensively evaluate and classify the horizontal shale well productivity combined with economic evaluation.

3.1 Productivity indicator

3.1.1 Normalized test production

The normalized test production refers to the constant well production within specified fluctuation ranges of the wellhead pressure, production rate and period. In field production operations, each shale gas well is generally tested by varying the production system in the initial flowback stage. The choke is adjusted from a small to a large aperture within a specific testing period to acquire the corresponding normalized test production, and the obtained normalized test production specifications are provided in Table 1. The normalized test production has been widely adopted in field production to preliminarily characterize the shale gas well productivity and determine reasonable production allocation schemes. In general, the shale gas wells in the Weiyuan shale gas field are tested for 30–90 days to determine the normalized test production. A normal and continuous shale gas well production mode is maintained after the test. Although the determination of the normalized test production is partly influenced by human factors, the normalized test production remains one of the major indicators to approximately understand the shale gas well productivity in the initial production stage (Meng et al., 2015; Gu et al., 2016; Guo, 2018; Xiao, 2018; Li et al., 2019; Ma et al., 2020).

Table 1 Normalized test production specification of the shale gas wells in the Weiyuan shale gas field

Normalized test production	Fluctuation range		Duration
	q_t	P_{WH}	
$q_t \geq 50 \times 10^4$ m^3/d	< 5%	⩽0.7 MPa	
20×10^4 m^3/d < q_t < 50×10^4 m^3/d	< 5%	⩽0.5 MPa	≥15d
$q_t \leq 20 \times 10^4$ m^3/d	< 5%	⩽0.3 MPa	

3.1.2 Flowback ratio (FBR_{165})

The fracturing fluid flowback ratio is also considered a vital indicator to characterize the fracturing treatment performance and well productivity. Field production data have indicated a positive correlation between the flowback ratio and production time and a negative correlation between the well productivity and flowback ratio (Li et al., 2016; Ghaderi and Clarkson, 2016; Clarkson et al., 2016; Zhang et al., 2017; Zou and Chu, 2018; Han et al., 2018). In general, less fracturing fluid is recovered from shale gas wells with a high gas production. Shale gas well flowback features a large volume and sharp decline in the initial flowback stage. The flowing casing pressure and flowback volume remain relatively low and stable after a rapid decline over approximately 90 days. In this paper, FBR_{165} is adopted as a productivity indicator in the Weiyuan shale gas field.

3.1.3 First-year initial production (IP_{330})

The first-year initial production is also considered a key indicator to describe the horizontal shale gas well productivity. When the initial production during a specific period is chosen as a productivity indicator, the implicit parameter is the pressure. Production and pressure are closely associated with shale gas well production. Shale gas production is accurately characterized only when the pressure remains stable by the end of the evaluation period. The flowing casing pressure should remain stable and low after 150–180 days without the tubing running operation. The tubing running operation usually leads to a casing pressure fluctuation from 90–240 days. Therefore, the first-year initial production is finally selected as a productivity indicator. Due to the tubing running operation, workovers and other well treatments, it is impossible to achieve a continuous well production. The statistical cumulative production and shut-in times in the first year were obtained for 126 horizontal shale gas wells in the Weiyuan shale gas field (Fig. 5). In addition to 2 abnormal production wells, the cumulative production time in the first natural year ranged from 290–365 days, and the corresponding average production time in the first year was approximately 340 days. According to the field development program, production was also designed based on 330 days in a calendar year. Therefore, IP_{330} is adopted as a productivity indicator. IP_{330} refers to the average daily gas production for 330 days after production initiation by removing shut-in data points.

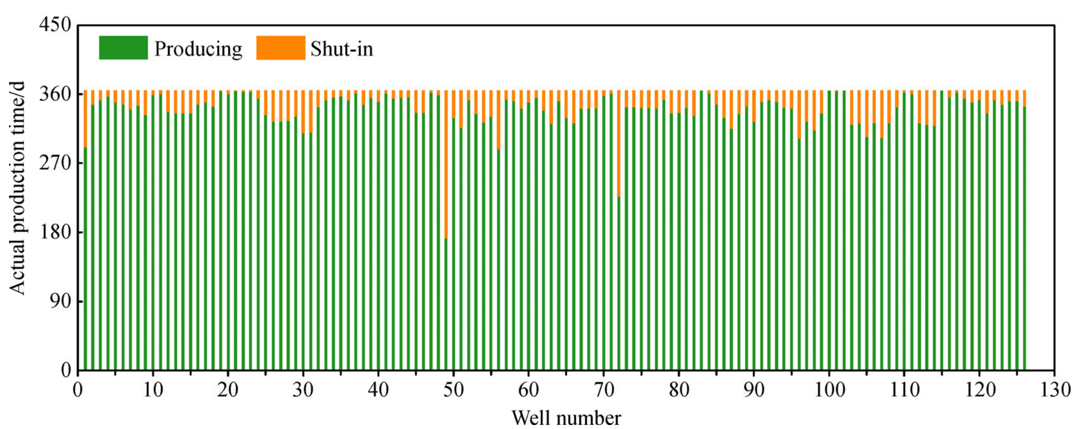

Fig. 5 Statistical cumulative production and shut-in times for the horizontal shale gas wells in the Weiyuan Shale Gas Field.

3.1.4 EUR

EUR is a vital indicator to measure the well productivity, which greatly influences the gas reservoir development performance and economic benefits (Zhao et al., 2019b; Xiong, 2019). EUR estimation of shale gas wells is largely dependent on the well production mode, flow regime, production history and operation conditions. Specific operation conditions must be followed to provide a reasonable estimation. In the past, almost all shale gas wells were put into production under constant-pressure conditions to recover their cost as soon as possible. Empirical production decline analysis has been widely adopted and provides a relatively reliable EUR estimation in this case. However, the shale gas well production rate and pressure are artificially constrained in the Weiyuan shale gas field to reduce the stress-sensitivity effect. Blasingame, normalized pressure integral (NPI), Agarwal-Gardner and Wattenbarger type curves, the flowing material balance (FMB) technique and numerical simulation were comprehensively applied to estimate EUR of the shale gas wells in this gas field.

3.2 Productivity evaluation

Statistical correlations between the normalized test production, flowback ratio (165 days), first-year initial production (330 days) and estimated single-well EUR in the Weiyuan Shale Gas Field were provided to analyze the horizontal shale gas well productivity. The normalized test production exhibited a relatively positive correlation with EUR (Fig. 6(a)), and the corresponding linear-correlation coefficient (R^2) reached 0.93. The normalized test production could be employed to preliminarily characterize the productivity of horizontal shale gas wells in the initial stage without a long production history. Although no deterministic correlation was determined between EUR and FBR_{165} in the Weiyuan shale gas field, horizontal shale gas wells with a high EUR usually indicated a low fracturing flowback ratio over 165 days (Fig. 6(b)). FBR_{165} could be adopted as a supplementary indicator to qualitatively characterize the fracturing performance and productivity. The first-year initial production exhibited a positive correlation with EUR, and the corresponding linear-correlation coefficient (R^2) reached up to 0.98 (Fig. 6(c)). The first-year initial production is an accurate indicator to characterize the well productivity in the Weiyuan shale gas field. The normalized test production also demonstrated a relatively positive correlation with the first-year initial production, which could be applied in the production allocation process of new production wells.

Four indicators were considered to establish a systematic method to evaluate the whole-life productivity of the horizontal shale gas wells in the Weiyuan shale gas field, and the corresponding workflow diagram is shown in Fig. 7. Various indicators are involved in productivity evaluation in the different production stages. When a new horizontal shale gas well is put into production, the normalized test production can be determined after approximately 30–90 days to preliminarily forecast the

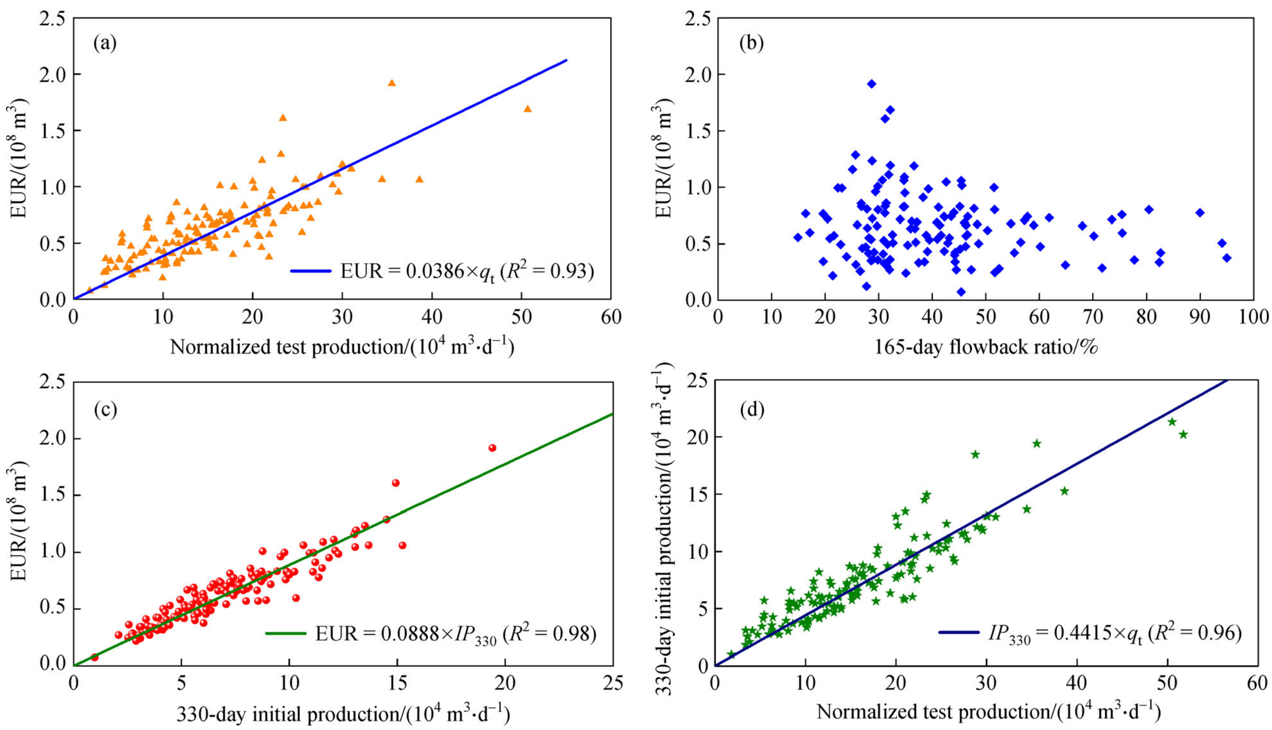

Fig. 6 (a) Relationship of the normalized test production with EUR; (b) relationship of FBR180 with EUR; (c) relationship of the first-year initial production with EUR; (d) relationship of the normalized test production with the first-year initial production.

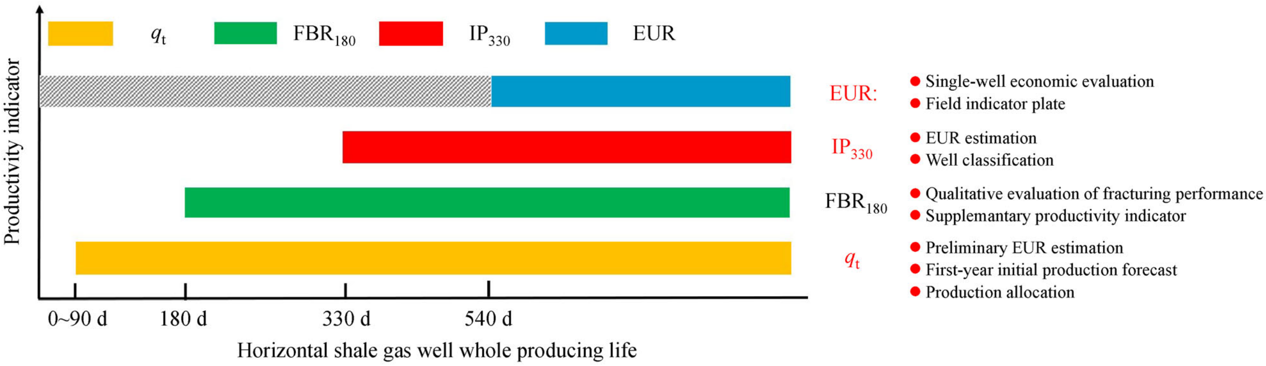

Fig. 7 Horizontal shale gas well productivity evaluation diagram for the Weiyuan shale gas field.

first-year initial production and single-well EUR. In addition, the normalized test production has been widely applied to allocate well production, and the initial well production rate is usually set to 30%–50% of the normalized test production. FBR_{165} is regarded as a supplementary indicator to characterize the well productivity and fracturing performance after approximately 165 days. IP_{330} is an essential and accurate productivity indicator in EUR estimation and productivity classification after 330 days. The estimated EUR can be applied in single-well economic evaluation and field preparations. In EUR estimation with Blasingame, NPI, Agarwal-Gardner and Wattenbarger type curves, the FMB technique and numerical simulation, the estimation certainty increases with the well production history. However, there is no definite determination of the required duration of a production history to obtain a relatively accurate EUR estimate (the gray bar in Fig. 7). According to production analysis experience in the Weiyuan shale gas field, a relatively accurate EUR could be obtained after 540 days. After the estimation of multiple wells, a series of templates could be designed based on analogy to roughly forecast the production of newly drilled wells before being put into production.

3.3 Sensitivity analysis of the productivity

Based on fine geological characterization, the $LM1_1$ submember is chosen as the development interval in the Weiyuan shale gas field. The corresponding four beds exhibit an increase in reservoir quality from top to bottom, and bed $LM1_1^1$ possesses the highest reservoir quality. Statistical data on the lateral target position and EUR of 48 horizontal wells in the Weiyuan shale gas field were acquired (Fig. 8(a)), and the lateral target interval was defined based on the distance from the bottom of bed $LM1_1^1$. A relatively high single-well EUR is attained when the target interval is close to the bottom of bed $LM1_1^1$. Almost all the target positions of the wells with EUR values exceeding 0.80×10^8 m^3 occur less than 5.0 m from the bottom of bed $LM1_1^1$. It should be noted that the thickness of bed $LM1_1^1$ also approximately ranges from 1.7–5.5 m in the Weiyuan shale gas field. According to reservoir evaluation as part of the original development program, $LM1_1^1$ exhibits the most favorable properties, followed by $LM1_1^2$ and $LM1_1^3$, while $LM1_1^4$ possesses the worst reservoir quality (Liu et al., 2018; Wang et al., 2019). The average reservoir thicknesses of $LM1_1^1$, $LM1_1^2$, $LM1_1^3$ and $LM1_1^4$ are 3.8, 5.5, 6.8 and 18.6 m, respectively. To maximize the reserve production level of the $LM1_1$ submember, horizontal wellbores were designed and drilled in the lower-middle part to produce the whole submember by artificial fracturing treatment. However, the horizontal wells drilled in the lower-middle part of the $LM1_1$ submember attained a low production performance. To enhance the single-well production performance, the horizontal wellbores were adjusted downward toward the high-quality reservoirs, and the development design was also adjusted to produce the $LM1_1^1$, $LM1_1^2$ and $LM1_1^3$ submembers rather than the whole $LM1_1$ submember. A series of horizontal well tests demonstrated that a high production performance could be reached by placing a horizontal wellbore within $LM1_1^1$ with the best reservoir quality among all $LM1_1$ submembers. It has been speculated that due to well-developed bedding features or other special properties of shale gas reservoirs, artificial fractures may be restricted and attain a relatively short propagation distance along the vertical direction during multistage fracturing. Horizontal wellbores should be placed within those beds with the highest reservoir quality as much as possible to achieve a high productivity. Based on field experience, the optimal lateral target interval was confirmed within bed $LM1_1^1$ to ensure a high well productivity.

According to the statistical correlations between the horizontal gas well EUR and drilling indicators in the Weiyuan shale gas field, the corresponding drilling length of bed $LM1_1^1$ is regarded as a key indicator during

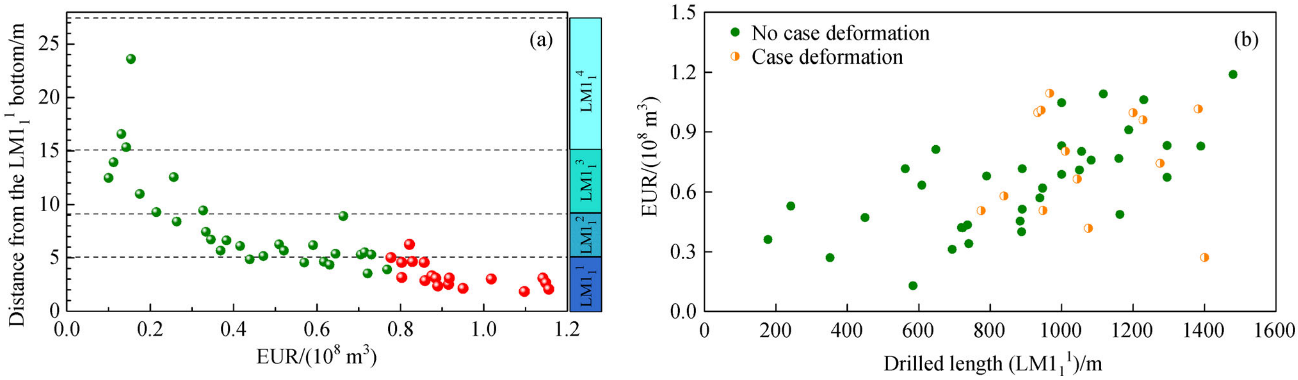

Fig. 8 Correlations between the horizontal gas well EUR and drilling indicators. (a) Lateral target interval; (b) drilling length of $LM1_1^1$.

horizontal shale gas well drilling operation. The field drilling lengths of bed $LM1_1^1$ were also evaluated based on stratigraphic correlation and logging interpretation, which revealed a positive correlation with EUR (Fig. 8(b)). This positive statistical relation also verifies the above understanding of the optimal lateral target interval. The single-well EUR is greatly dependent on the drilling length of bed $LM1_1^1$, which is regarded as the dominant productivity factor in regard to well productivity. In addition, the productivities of certain wells with large drilling lengths of bed $LM1_1^1$ were also influenced by casing deformation during multistage fracturing operations (the orange data points in Fig. 8(b)). In the initial development stage of the Weiyuan shale gas field, multistage fracturing operation led to casing deformation of different levels in many horizontal shale gas wells. Casing deformation usually occurred close to point A of the horizontal wellbore, and it was proposed that the casing strength and complex geostress are the major reasons. Point A refers to the location of the horizontal well trajectory entering the reservoir of interest. The casing strength of the buildup section is lower than that of the horizontal section, and casing deformation is most likely to occur around point A. In regard to horizontal wells with serious casing deformation, general fracturing without stage separation had to be carried out in the lateral sections, which led to a relatively low production performance. Therefore, wellbore integration is also regarded as a major productivity factor in the Weiyuan shale gas field. During development program adjustment, two countermeasures were adopted to prevent casing deformation, including increasing the casing strength and reserving part of the section after point A for multistage fracturing treatment.

The horizontal shale gas well productivity is highly dependent on the lateral target interval, drilling length of bed $LM1_1^1$ and wellbore integrity in the Weiyuan Shale Gas Field. To enhance the single-well production performance and EUR, the lateral target interval should be set within bed $LM1_1^1$. In addition, a large drilling length of bed $LM1_1^1$ and high wellbore integrity without casing deformation are necessary to attain a favorable production performance and EUR.

4 Discussion

The productivity of horizontal shale gas wells is dependent on a series of complex factors, including geological, reservoir, engineering, and production factors. The geological factors include the structure, fault, buried depth, stratum, bed thickness, and sedimentation environment. The reservoir properties consist of the TOC content, reservoir space classification, porosity, gas saturation, total gas content, geostress, rock mechanics, brittle mineral content, reservoir pressure and temperature. The engineering factors include the lateral length, high-quality drilled length, wellbore stability, wellbore trajectory smoothing level, hydraulic fracturing length, fracturing fluid intensity, proppant intensity, pumping rate, etc. The production factors are usually involved in the shale gas well production system (with or without pressure restriction during production), tubing operation timing, bubble drainage and other enhanced gas recovery treatments. The former two aspects are inherent properties of any shale gas reservoir, which are not subject to human influence. In regard to these inherent properties, TOC, porosity, brittle mineral content and total gas content were selected to comprehensively classify the reservoir in the Weiyuan shale gas field. The latter two aspects are considered artificial factors, which could be optimized to improve the well productivity. The lateral length, high-quality reservoir drilled length, fracturing fluid intensity, proppant volume intensity and pumping rate are related to the well productivity. Whether the pressure of shale gas wells should be restricted during production remains controversial. Scholars have proposed the pressure-restriction production pattern, which could decelerate the closure of artificial fractures and mitigate the stress-sensitivity effect. Other scholars have recommended production without pressure restrictions to accelerate the production of the adsorbed gas within the stimulated reservoir volume. Pressure restriction is a critical issue that needs to be further examined using different methods and means.

5 Conclusions

Based on production performance analysis of the Weiyuan Shale Gas Field, a practical and reliable evaluation method including the normalized test production, flowback ratio, first-year initial production and EUR was proposed to characterize the horizontal shale gas well productivity and identify the corresponding dominant productivity indicators, and the following conclusions are reached:

1) There exist positive linear correlations between the normalized test production, first-year initial production and EUR. The normalized test production is a major productivity indicator in the initial production stage. The first-year initial production is considered the most accurate productivity evaluation indicator after a year.

2) Almost all wells with relatively high productivities attain a relatively low fracturing fluid flowback ratio for equal production times. The flowback ratio could be considered a supplementary indicator to qualitatively represent the well productivity and fracturing performance.

3) The lateral target interval of the horizontal well, drilling length of $LM1_1^1$ and wellbore integrity are regarded as the dominant productivity factors in the Weiyuan Shale Gas Field in the Sichuan Basin.

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