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Research on the influencing factors of estimated ultimate recovery after shale gas well fracturing

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Abstract:

Before developing and producing a shale gas resource, it is critical to research estimated ultimate recovery (EUR). This research splits shale gas well production into five flow stages, to better understand the variables influencing EUR following shale gas fracturing and qualitatively evaluate the effect degree of each element on EUR. We fully examine contemporary research on the influencing variables of EUR following shale gas fracturing from three perspectives: geology, engineering, and production, and explain in detail 13 major regulating parameters impacting EUR in different flow phases. Based on the analytic hierarchy process (AHP), an evaluation model for the primary regulating elements of EUR following shale gas fracturing has been constructed. To test the novel model, actual data from production wells in a shale gas field in China was used. The optimal well for the current production system after shale gas fracturing is determined, and suggestions and improvement directions for the remaining gas wells' production systems are proposed.

Keywords: Shale gas well; EUR; Influencing factors; Analytic Hierarchy Process; Shale gas fracturing

1. Introduction

Shale gas resources have emerged as an important energy source in recent years [1]. In China, shale gas reserves are abundant, widely distributed, and highly valued in exploration and development [2–5]. The evaluation of EUR has significant guiding significance for large-scale, cost-economy, and efficient exploitation of shale gas reservoirs [6–8].

Currently, the factors influencing EUR can be studied in three categories: geology, engineering, and production [9]. Among geological factors, kerogen is an important material for generating shale gas [10]. The generated shale gas is mainly stored underground in free and adsorbed states [11, 12]. Because the matrix porosity and permeability of shale gas reservoirs are very low [13], and lower matrix permeability also makes it more difficult for free shale gas and shale gas desorbed after a certain period of production to flow in the reservoir, resulting in low shale gas production [14]. Therefore, horizontal wells often exploit shale gas reservoirs [15], and large-scale fracturing measures are taken. Fracture length [16–19], number of fractures [21, 22], fracture spacing [19], fracture conductivity [23–25], proppant dosage [26, 27], SRV radius [28, 29], length of the horizontal section [30], Langmuir volume, pressure [15–19, 21–28], skin factor [22] and other engineering parameters affect the exploitation of shale gas strongly. However, which of these factors can affect the EUR of shale gas wells needs to be discussed and summarized in detail, and there is no specific research on the degree of influence of each factor on EUR.

During the production period of shale gas wells, there are multiple flow stages in staged fracturing horizontal wells in shale reservoirs. Cinco-Ley proposed the concept of bilinear flow for the first time [31]. The model assumes that the three flow regions are linear flow. Brockenbrough and Lee et al.proposed a trilinear flow model based on the bilinear flow model [32]. This trilinear flow model mainly studies the influence of fracture half-length and fracture conductivity on the well test pattern curve of oil and gas wells after fracturing. Ozkan found that linear flow is dominant in low permeability formations. The constructed trilinear flow model is relatively simple, but does not consider the adsorption, desorption and diffusion of shale gas [33]. Zhu Qin constructed a trilinear flow model of dual-medium shale gas [34]. It also analyzes the sensitivity of channeling coefficient, storage capacity ratio, adsorption coefficient and apparent permeability coefficient. Xie Weiyang considered the influence of shale gas desorption. By constructing a dual medium model of shale gas, the flow stage of shale gas horizontal wells is divided into seven flow stages from the late stage of wellbore storage to the controlled flow of reservoir outer boundary [35]. Liu Wenchao et al.divided the shale gas production stage into five flow stages according to the pseudo pressure calculated by deconvolution [36]. However, the above scholars have put the division of the flow evolution stage of shale gas staged fracturing horizontal wells on the theoretical research. What are the influencing factors at each stage, what are the effects on the EUR of shale gas wells, and how much the specific impact is not systematically studied.

In order to be more practical and easy to calculate, we use Liu's classification criteria to divide it into five flow stages, as shown in Figure 1. However, the EUR influencing factors in these five stages still lack a systematic summary and arrangement, and they have not been well combined and analyzed with geological, engineering, and production factors.

To get a better understanding of the influencing elements of shale gas EUR, this paper comprehensively studies the influencing factors of shale gas EUR from three aspects: geology, engineering, and production. The influencing variables of shale gas reservoir EUR in each step are presented in five stages Fig. 1. The influencing factors of EUR after shale gas well fracturing are closely linked with the flow stage. Applying the analytic hierarchy process (AHP), a mathematical model of the hierarchical structure was established, the contribution weight of each main control factor to EUR was calculated, and the main control factors affecting EUR after shale gas well fracturing were identified. Combined with the actual production data of the three wells A_1, A_2 and A_3, the production system of the three wells was optimized, which laid a foundation for realizing large-scale, economical, and effective development of shale gas reservoirs and also creates the groundwork for enhancing the EUR of individual wells.

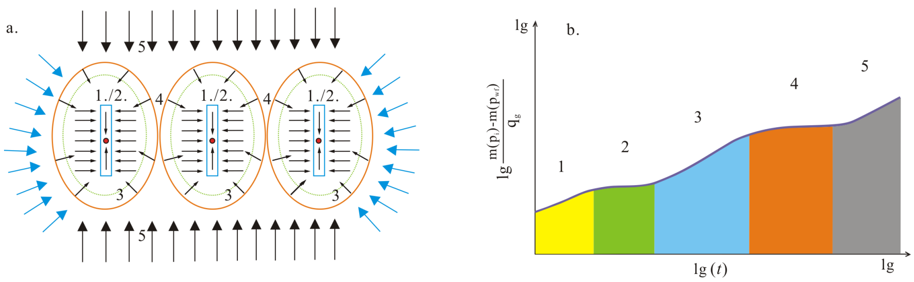
2. Analysis of influencing factors

2.1 Geological factor analysis

Since the original total organic carbon (TOC) content has different effects on EUR in different regions, it is generally positively correlated with EUR in high-yielding regions [20]. Currently, relevant scholars have only researched the Bakken region of the United States, which has great limitations. The burial depth of shale gas is dependent on characteristics such as kerogen concentration, making the model presented in this research excessively complicated. However, there is no relevant literature to demonstrate the specific relationship between porosity, gas saturation, and brittle mineral content in the five flow stages of shale gas well production. Zhang et al. also discovered through numerical simulation studies that rock compressibility is less responsive to gas production [37]. Consequently, the original TOC content, reservoir burial depth, porosity, gas saturation and rock compressibility are not thoroughly discussed in this paper.

Kerogen, as a source rock for generating shale gas, has an impact on EUR at all stages when its content increases by 10%, and its contribution to total shale gas production increases by about 12% [10]. A certain amount of pressure will be generated in the reservoir as shale gas is produced. Cao et al. illustrate that the initial pressure of gas formation and start pressure gradient are proportional to the cumulative gas production of shale gas [22].

As production time increases, shale gas migrates from the matrix to the fractures and then flows into the wellbore [38]. From the linear flow of shale gas perpendicular to the fracture to the diffusion of the discharge area to the outer boundary, the average permeability of the matrix will have an impact on EUR. Shale gas migrates from the matrix to the fractures and then flows into the wellbore as production



1.Early linear flow 2.Early radial flow 3.Fracture boundary flow 4.Compound linear flow 5.System radial flow

Figure 1. Schematic diagram of flow state and corresponding pressure derivative curve of staged fracturing horizontal well [20].

time increases [38]. The average permeability of the matrix will influence EUR from the linear flow of shale gas perpendicular to the fracture to the diffusion of the discharge area to the outer boundary. For matrix average permeability, the greater the average permeability of the matrix, the greater the EUR [13]. The cumulative thickness of storage layers is proportional to the cumulative production capacity, and has a greater impact in the 4th flow stage, where the pressure derivative curve lasts longer [21].

The relationship between geological factors and EUR is summarized in Table 1. With the exception of the start pressure gradient, all other geological factors are positively correlated with EUR, as shown in Table 1. EUR was impacted in five phases by the kerogen concentration, start pressure gradient, average permeability of the matrix, and initial pressure of gas formation. The cumulative thickness of the reservoir influences the cumulative production of shale gas wells in four stages, from stage 2 to 5 of the flow.

2.2 Engineering factor analysis

Due to the slippage effect and matrix Knudsen diffusion, gas production has a greater impact in the middle stage of production in the engineering factor analysis [10]. The channeling coefficient and elastic storage capacity have a certain influence on gas production in the flow stage 2 [39]. Fracture conductivity affects gas production from stage 2 to 4 of the flow [23, 24]. At the same time, shale gas is often exploited in horizontal wells, the multi-stage fractured horizontal well technology has been widely used in shale gas reservoirs [40] and the type of well is relatively fixed. The proppant is commonly composed of quartz sand in shale gas hydraulic fracturing. The amount of fracturing fluid deviates from the design amount due to the leakage of fracturing fluid, and is also influenced by the number of fracturing stages. In addition, there are no relevant references on the type and amount of proppant, the amount of fracturing fluid, or the number of fracturing stages. As a result, when analyzing the influencing factors of EUR after shale gas fracturing, we do not take nine factors into account.

Shale reservoirs often need to be developed through fracturing [17]. The longer the fracture length produced by fracturing, the slower the initial production decline and the faster the later production decline [16]. The number of fracture bars has a significant effect on production [41]. The fracture length and number of fractures have impact on gas well productivity from stage 1 to 5 of the flow [18, 19, 22]. Among them, the fracture length has the greatest impact on cumulative production in the early stage [42].In addition, the effect of fracture spacing on EUR begins with flow stage 2 [21] and is greatest in flow stage 3 [19]. In comparison to natural fractures, SRV fracture networks have higher conductivity [43]. The radius of the SRV area mainly affects the stage 2 to 4 of the flow [44]. The cumulative gas production increases as the SRV radius increases; Jian et al. believe it has an optimal value [28], but the optimal value has not been solved, necessitating further research. Wei et al. analyzed the impact of permeability in the SRV area on the production profile and confirmed that it contributes significantly to shale gas production in the early linear flow to composite linear flow stages [45].

Xu et al. predicted two adsorption isotherms with Langmuir pressure of 300 PSI and Langmuir pressure of 1500 PSI respectively [15]. It demonstrates that when the Langmuir pressure increases, more adsorbed gas is liberated and the gas output increases. The cumulative production is affected by the length of the horizontal section from stage 1 to 3 of the flow [30]. In addition, the flow stage 2 occurs earlier with longer horizontal segments. The skin factor and EUR have a negative correlation and are both important in the transition from stage 1 to 4 of the flow [18].

Table 2 shows the association between engineering factors and EUR. With the exception of the negative correlation between crack spacing and skin coefficient and EUR, all other geological factors are positively correlated with EUR, and crack length, number of cracks, Langmuir volume, and pressure all have a five-stage influence on EUR. The fracture spacing influences the cumulative production of shale gas wells in four stages, from stage 2 to 5 of the flow; the SRV radius influences EUR from flow stage 2 to 4; and also the horizontal section length and skin factor influence EUR from stage 1 to 3 of the flow.

2.3 Production factor analysis

Production factors are critical in ensuring long-term stable production of gas wells [13, 30]. There are many sources of liquids discharged from shale gas layers, such as edge and bottom water in the same layer, drilling fluid leakage, and fracturing fluid retention. It is difficult to determine which liquid affects EUR only based on the liquid production volume. The effect of liquid production on EUR is not discussed in detail.

As shown in Figure 2, if a large amount of mining is done early on and the gas production rate is greater than 5%, the stable production time and recovery degree will both decrease [42]. The stress sensitivity index is negatively correlated with EUR, and both the gas recovery rate and the stress sensitivity index influence EUR at all stages of

Table 1. Summary table of the relationship between geological factors and EUR.

Influencing factors	Correlation with EUR	Impact stage
Kerogen content	Positive correlation	All stages
Initial pressure of gas formation	Positive correlation	All stages
Start pressure gradient	Negative correlation	All stages
Average permeability of the matrix	Positive correlation	All stages
Cumulative thickness of reservoir	Positive correlation	Stage 2 to 5 of the flow

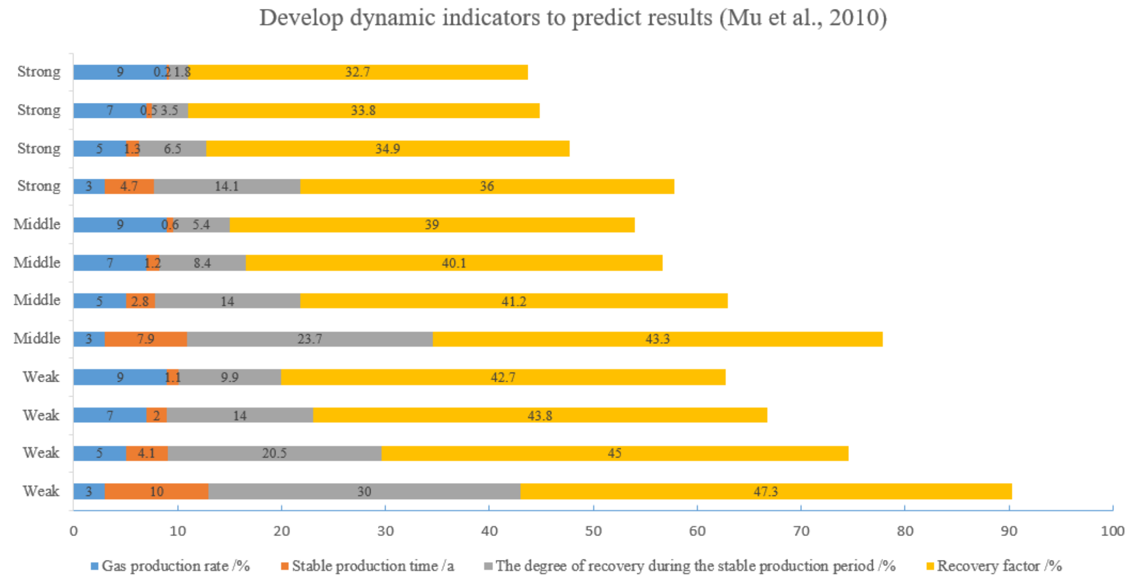


Figure 2. Develop dynamic indicators to predict results.

production. The relationship between production factors and EUR is shown in Table 3.
Therefore, it can be inferred that, as shown in Table 3, the key production parameters affecting shale gas well EUR are the gas production rate and stress sensitivity index.

3. Quantification methodes and models

3.1 Comprehensive analysis of influencing factors in each flow stage

The flow evolution process of shale gas well production is currently split into five stages, according to Liu et al [20]. Division method: from stage 1 to 5 of the flow. Table 4 displays the determining elements for each step.

As observed in Table 4, a variety of factors have an impact on EUR during stages 2 and 3 of the flow. Early in the production cycle, the output of shale gas wells drops quickly; subsequently, it slows down. Therefore, the primary driving forces for EUR should be identified at an early stage of shale gas development. In order to better utilize shale gas and increase the EUR of shale gas wells, the development plan should be modified in accordance with the major regulating elements. Since there are many factors affecting EUR in shale gas wells, each factor has a different degree of influence on EUR in different flow stages. Additionally, each element has a definite association with the others. It is required to further assess the significance of each contributing element at each stage when EUR is assessed for shale gas development.

3.2 Construction of mathematical models

AHP was first proposed by Saaty [46, 47]. It transforms complex problems into hierarchical structures that may quickly and accurately evaluate the relative weights of various aspects in a comprehensive evaluation problem. It has the advantages of being systematic, practical, concise, and effective when compared to principal component analysis

Table 2. Summary table of engineering factors and EUR influencing factors.

Influencing factors	Relationship with EUR	Impact stage
Fracture length	Positive correlation	All stages
Number of fractures	Positive correlation	All stages
Fracture spacing	Negative correlation	Stage 2 to 5 of the flow
SRV radius (volume)	Positive correlation	Stage 2 to 4 of the flow
Langmuir volume, pressure	Positive correlation	All stages
Length of horizontal	Positive correlation	Stage 2 to 4 of the flow
Skin factor	Negative correlation	Stage 2 to 4 of the flow

Table 3. Summary table of the relationship between production factors and EUR.

Influencing factors	Relationship with EUR	Impact stage
Gas production rate	Negative correlation	All stages
Stress sensitivity index	Negative correlation	All stages

Table 4. Summary of factors affecting each stage of five flow stages during the production of shale gas wells.

Flow stage 1	Flow stage 2	Flow stage 3	Flow stage 4	Flow stage 5
Kerogen content Initial pressure of gas formation Start pressure gradient Average permeability of the matrix Fracture length Number of fractures Langmuir volume, pressure Length of horizontal section Skin factor Gas production rate Stress Sensitivity Inde	Kerogen content Initial pressure of gas formation Cumulative thickness of reservoir Start pressure gradient Average permeability of the matrix Fracture length Number of fractures Fracture spacing SRV radius (volume) Langmuir volume, pressure Length of horizontal section Skin factor Gas production rate Stress Sensitivity Index	Kerogen content Initial pressure of gas formation Cumulative thickness of reservoir Start pressure gradient Average permeability of the matrix Fracture length Number of fractures Fracture spacing SRV radius (volume) Langmuir volume, pressure Length of horizontal section Skin factor Gas production rate Stress Sensitivity Index	Kerogen content Initial pressure of gas formation Cumulative thickness of reservoir Start pressure gradient Average permeability of the matrix Fracture length Number of fractures Fracture spacing SRV radius (volume) Langmuir volume, pressure Length of horizontal section Skin factor Gas production rate Stress Sensitivity Index	Kerogen content Initial pressure of gas formation Cumulative thickness of reservoir Start pressure gradient Average permeability of the matrix Fracture length Number of fractures Fracture spacing Langmuir volume, pressure Gas production rate Stress Sensitivity Index

and the entropy method, and it has been widely used in economic, military, energy, and other fields [48]. It solves the problems of tight gas drainage and gas recovery process optimization [49]. As a result, we chose the AHP to build a mathematical model and screen out the main controlling factors of EUR, which will be useful in developing shale gas fields and improving EUR.
The main steps of AHP are as follows:
(1) Construct a hierarchy that represents the decisional problem.
(2) Construct the judgment matrix A=(a_{ij}).
Among them, the importance of each element in the judgment matrix is shown in Table 5.
(3) Use the square root method to solve the weight of each index. Multiply the elements of each row of the judgment matrix and open it to the nth power, and obtain the weight vector M through normalization:

$$M_i = \frac{(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}}{\sum_{i=1}^{n}(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}} \tag{1}$$

(4) Carry out a consistency check. Only verification can show that the judgment matrix is logically reasonable, and then the results can be analyzed continuously. The consistency check is as follows:

$$CI = \frac{\sum_{i=1}^{n} \frac{I_i W}{n W_i} - n}{n-1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

Among them, W=(W_1, W_2, ..., W_n)^T, vector I is the row vector of the judgment matrix A, and Ii represents the ith row vector of A.
For the n order matrix, the RI value can be found in Table 6

Table 5. Judgment matrix importance value table.

a_{ij} value	Express meaning
1	The i is as important as j
3	The i is slightly more important than j
5	The i is significantly more important than j
7	The i is strongly more important than j
9	The i is extremely important than j
2, 4, 6, 8	The median value of adjacent judgment indicators
1/2, 1/3, ...,1/9	The relevance of j and i is the reverse of what is stated above

Table 6. Consistency check RI table.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

[48].
If $CR < 0.1$, then the consistency test is satisfied. If $CR > 0.1$, there is serious inconsistency, and the judgment matrix needs to be readjusted until $CR < 0.1$.
Figure 3. Shows the hierarchical structure model of the main controlling factors affecting EUR after shale gas fracturing is established.

4. Model application

The target area is located in the west of the North China Block. The structure in the basin is gentle, the subsidence is stable, and the overall appearance of regional slope is upturned in the east and plunging in the west. The average thickness of sedimentary rock is about 5000 m. D-J block is located in the upper Paleozoic coal-accumulating depression, with coal rock thickness of 5-17 m and dark mudstone thickness of 80-120 m. There are many layers of coal and rock with stable distribution and good continuity.
According to the model of main controlling factors affecting EUR after shale gas fracturing established above, the main controlling factors affecting EUR were selected, and combined with the exploration and development data of three selected wells in a shale gas field in China, the optimal wells with the production system were selected. The actual data of the three wells are shown in Table 7.
Calculation of weights for factors influencing EUR:
(1) Calculate the first layer, i.e. geological, engineering, and production factor weights.
Structural geology, engineering, production factor scoring table (Table 8), and judgment matrix B:

$$B = \begin{bmatrix} 1 & \frac{1}{4} & 2 \\ 4 & 1 & 5 \\ \frac{1}{2} & \frac{1}{5} & 1 \end{bmatrix} \tag{4}$$

According to Eqs. (4), it can be known that the maximum characteristic root of the judgment matrix B $\lambda_{\max}$ =3.0246. Besides, CI=0.0123, CR=0.0212<0.1, satisfy the consistency check. Among them, the weights of geological, engineering and production factors of the first layer are: 0.19981 , 0.68334 , 0.11685.

(2) Calculate the weight of the second layer of geological, engineering, and production factors.
According to the calculation method steps of the first layer, the scoring table (Table 9, Table 10, Table 11) and judgment matrix (C, D, E) of geological factors, engineering factors, and production factors of the second layer are respectively constructed as follows:

$$C = \begin{bmatrix} 1 & 2 & 2 & \frac{1}{2} & \frac{3}{2} \\ \frac{1}{2} & 1 & \frac{2}{3} & \frac{1}{3} & \frac{2}{3} \\ \frac{1}{2} & \frac{3}{2} & 1 & \frac{2}{5} & \frac{2}{3} \\ 2 & 3 & \frac{5}{2} & 1 & 2 \\ \frac{2}{3} & \frac{3}{2} & \frac{3}{2} & \frac{1}{2} & 1 \end{bmatrix} \tag{5}$$

$$D = \begin{bmatrix} 1 & \frac{2}{5} & \frac{1}{2} & \frac{1}{3} & \frac{3}{2} & \frac{2}{4} \\ \frac{5}{2} & 1 & 2 & \frac{2}{3} & 3 & \frac{2}{5} \\ 2 & \frac{1}{2} & 1 & \frac{1}{2} & \frac{5}{2} & \frac{1}{2} \\ 3 & \frac{3}{2} & 2 & 1 & 4 & \frac{3}{2} \\ \frac{2}{3} & \frac{1}{3} & \frac{2}{5} & \frac{1}{4} & 1 & \frac{2}{7} \\ \frac{7}{2} & \frac{5}{2} & 2 & \frac{2}{3} & \frac{7}{2} & 1 \end{bmatrix} \tag{6}$$

$$E = \begin{bmatrix} 1 & \frac{1}{2} \\ 2 & 1 \end{bmatrix} \tag{7}$$

The CR values of C, D and E are 0.00813,0.01997 and 0 are less than 0.1, respectively.
(3) The final weight calculation of each factor.
According to the calculation results of steps (1) and (2), the weight of each factor in the second layer is multiplied by the weight of the geological, engineering, and production factors in the first layer to obtain the final weight of each factor (Table 12).
It can be seen from Table 12 that the SRV radius (volume), the length of the horizontal section, and the number of fractures affect the EUR after the shale gas fracturing extremely, and can be used as the main controlling factors for the EUR after the shale gas fracturing; the start pressure gradient and initial gas reservoir pressure has the lowest weight and has a weak effect on EUR after shale fracturing.
The five flow stages scoring table (Table 13) and judgment matrix F are constructed as follows:

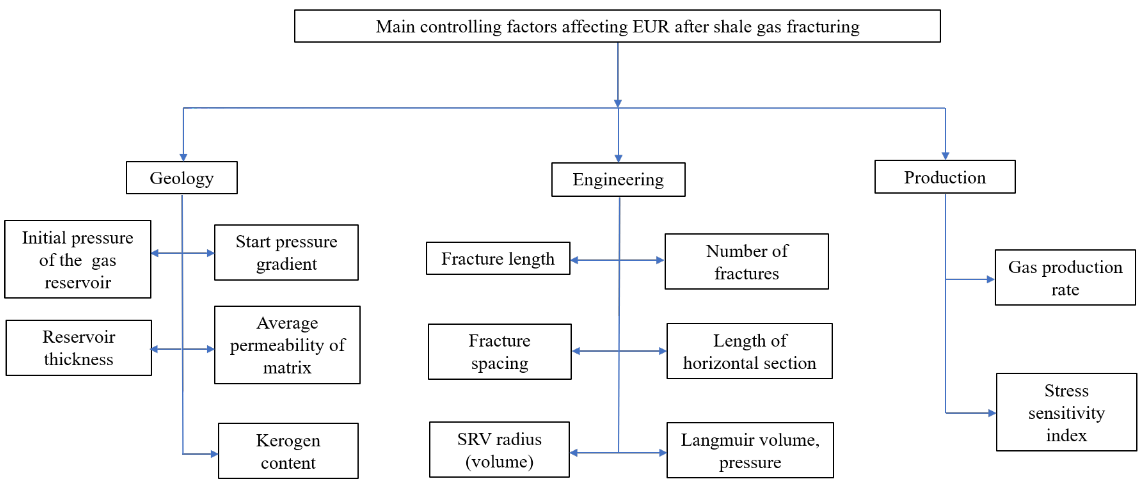


Figure 3. Hierarchical structure model diagram of main controlling factors affecting EUR after shale gas fracturing.

Table 7. A_1, A_2, A_3 Three wells basic datasheet.

Factor	A_1	A_2	A_3
Cumulative thickness of reservoir/m	4	9	6
Kerogen content/%	1.78	2.44	2.17
Start pressure gradient/MPa/m	0.059	0.056	0.048
SRV/$10^6 m^3$	23.46	3.58	3.43
Initial pressure of gas formation/MPa	20.6	12.7	17.5
Average permeability of the matrix/mD	0.00294	0.0025	0.002
Fracture length/m	144	280	300
Number of fractures/strip	9	3	5
Fracture spacing/m	8	15	12
Length of horizontal section/m	1760	300	1070
Gas production rate/%	4.2	3.6	3.8

Table 8. The first layer of the geological, engineering, and production factor scoring table.

Factor	Geology	Project	Production
Geology	1	1/4	2
Project	4	1	5
Production	1/2	1/5	1

Table 9. The second layer of geological factors scoring table.

Factor	Kerogen content	Initial pressure of gas formation	Start pressure gradient	Average permeability of the matrix	Cumulative thickness of reservoir
Kerogen content	1	2	2	1/2	3/2
Initial pressure of gas formation	1/2	1	2/3	1/3	2/3
Start pressure gradient	1/2	3/2	1	2/5	2/3
Average permeability of the matrix	2	3	5/2	1	2
Cumulative thickness of reservoir	2/3	3/2	3/2	1/2	1

Table 10. Scoring table for each factor of the second-tier project.

Factor	Fracture length	Number of fractures	Fracture spacing	SRV radius (volume)	Langmuir volume, pressure	Length of horizontal section
Fracture length	1	2/5	1/2	1/3	3/2	2/7
Number of fractures	5/2	1	2	2/3	3	2/5
Fracture spacing	2	1/2	1	1/2	5/2	1/2
SRV radius (volume)	3	3/2	2	1	4	3/2
Langmuir volume, pressure	2/3	1/3	2/5	1/4	1	2/7
Length of horizontal section	7/2	5/2	2	2/3	7/2	1

Table 11. The second-level production factor scoring table.

Factor	Gas production rate	Stress Sensitivity Index
Gas production rate	1	1/2
Stress Sensitivity Index	2	1

Table 12. The final weight value table of each factor.

Factor	Total weight value	Factor	Total weight value
SRV radius (volume)	0.19067	Kerogen content	0.04540
Length of horizontal section	0.18199	Langmuir volume, pressure	0.04220
Number of fractures	0.12356	Gas production rate	0.03895
Fracture spacing	0.09068	Cumulative thickness of reservoir	0.03440
Stress sensitivity index	0.07790	Start pressure gradient	0.02641
Average permeability of the matrix	0.07195	Initial pressure of gas formation	0.02165
Fracture length	0.05423		

Table 13. Scoring table for each flow stage.

Flow stage	Flow stage 1	Flow stage 2	Flow stage 3	Flow stage 4	Flow stage 5
Flow stage 1	1	4/5	3/2	1/2	5/4
Flow stage 2	5/4	1	5/4	2/5	3/2
Flow stage 3	2/3	4/5	1	2/5	5/4
Flow stage 4	2	5/2	5/2	1	5/2
Flow stage 5	4/5	2/3	4/5	2/5	1

$$F = \begin{bmatrix} 1 & \frac{4}{5} & \frac{3}{2} & \frac{1}{2} & \frac{5}{4} \\ \frac{5}{4} & 1 & \frac{5}{4} & \frac{2}{5} & \frac{3}{2} \\ \frac{2}{3} & \frac{4}{5} & 1 & \frac{2}{5} & \frac{5}{4} \\ 2 & \frac{5}{2} & \frac{5}{2} & 1 & \frac{5}{2} \\ \frac{4}{5} & \frac{2}{3} & \frac{4}{5} & \frac{2}{5} & 1 \end{bmatrix} \tag{8}$$

The maximum characteristic root $\lambda_{\max}$ =5.23544, CI=0.05886, CR=0.05255 $<$ 0.1 of the judgment matrix F is obtained, which satisfies the consistency test. The weights of stage 1 to 5 of the flow are: 0.17218, 0.18004, 0.14001, 0.37651 and 0.12806. It can be seen that the weight value of the 4th flow stage is the largest, and the weight values of the flow stage 1 and flow stage 2 are equal, followed by the flow stage 3 weight, and the flow stage 5 has the lowest weight value.

From Table 12 and the weight value of each flow stage, the final weight value of each factor in different flow stages can be obtained as shown in Table 14.

Combining the weight values of each stage and Table 14, we can conclude:

(1) From a longitudinal perspective, the weight values of nearly all elements achieve their maximum values in the transition from stage 2 to 4 of the flow, while the SRV radius (volume) weight value reaches its greatest value in the 4th flow stage. The system's weight of the total number of fractures is greatest at the radial flow stage. The flow stage 5 is where these parameters are least important, with the initial pressure of gas formation, start pressure gradient, and other components all having small weights in the other four flow stages. Due to the fact that the real production process involves a protracted flow stage 3. As a result, the SRV radius (volume) can be increased from stage 3 to 4 of the flow, the number of fractures can be increased, and fracture spacing can be reduced to increase the EUR of a single well in the flow stage 5.

(2) From a lateral perspective, the weights of flow stage 2 and flow stage 1 are equal and come in second place only to flow stage 3. In the flow stage 1, the length of the horizontal section has the highest weight. we can increase the single-well EUR by lengthening the horizontal section, increasing the number of fractures, increasing the length of the fractures, and decreasing the gas production rate in the stage 2 and 4 of the flow.

Based on the final weight of each factor and Table 7, the comprehensive scores of wells A_1, A_2 and A_3 under five flow stages can be calculated as shown in Table 15:

Based on the comprehensive scores of the three wells in each flow stage, it can be determined that the five flow stages of the three wells have the following characteristics:

(1) Vertically, the current production system's superiority order is $A_1 > A_2 > A_3$ under the whole score of the current preferred EUR impact index following shale gas fracturing.

(2) Horizontally, the three wells in the 4th flow stage have the highest weight values and finally stage 3 and 5 of the flow. However, the optimization and modification of the three wells should be concentrated on these two flow stages due to the lengthy duration of the stage 3 and 4 of the flow. Table 14 shows that the SRV radius (volume), the length of the horizontal segment, the number of fractures, and the fracture spacing have larger weight values in the stage 3 and 4 of the flow. Even though the remaining three flow stages only last a short while, changing these settings will still have an effect on the single well EUR.

(3) When stage 3 and 4 of the flow are present, well A_2 can, technically speaking, increase the SRV radius (volume). Additionally, since the well's horizontal section length is only 300 meters and the stage 1 and 2 of the flow have high weight values, increasing the horizontal section in these two stages can increase the well's EUR. By increasing the SRV radius (volume) in stage 3 and 4 of the flow, increasing the number of fractures in stage 1 and 2 of the flow, and decreasing the fracture spacing in the flow stage 5, well A_3 can increase the EUR of this well. In terms of production, the gas production rate has the highest weight value in the 4th flow stage when compared to other flow stages. Wells

Table 14. The final weight value table of each factor in the five flow stages.

Factor	Flow stage 1	Flow stage 2	Flow stage 3	Flow stage 4	Flow stage 5
SRV radius (volume)	-	0.03433	0.02670	0.07179	-
Length of horizontal section	0.03134	0.03277	0.02548	0.06852	-
Number of fractures	0.02128	0.02225	0.01730	0.04652	0.01582
Fracture spacing	-	0.01633	0.01270	0.03414	0.01161
Stress sensitivity index	0.01341	0.01403	0.01091	0.02933	0.00998
Average permeability of the matrix	0.01239	0.01295	0.01007	0.02709	0.00921
Fracture length	0.00934	0.00976	0.00759	0.02042	0.00694
Kerogen content	0.00782	0.00817	0.00636	0.01709	0.00581
Langmuir volume, pressure	0.00727	0.00760	0.00591	0.01589	0.00540
Gas production rate	0.00671	0.00701	0.00545	0.01467	0.00499
Cumulative thickness of reservoir	-	0.00619	0.00482	0.01295	0.00441
Start pressure gradient	0.00455	0.00476	0.00370	0.00994	0.00338
Initial pressure of gas formation	0.00373	0.00390	0.00303	0.00815	0.00277

Table 15. Comprehensive score table of three wells A_1, A_2 and A_3 in each flow stage.

well	Overall ratings				
	Flow stage 1	Flow stage 2	Flow stage 3	Flow stage 4	Flow stage 5
A_1	57.72439	60.35950	46.93920	126.22727	42.93289
A_2	12.57463	13.14866	10.22519	27.49723	9.35246
A_3	36.80001	38.47993	29.92432	80.47143	27.37025

A_2 and A_3 should slow down gas production in the 4th flow stage, increasing the EUR of the two wells.

5. Conclusion

Firstly, we review the influencing factors of EUR from geology, engineering and production. We analyze that kerogen content, initial pressure of gas formation, start pressure gradient, average matrix permeability, fracture length, number of fractures and Langmuir volume, pressure all affect EUR in five flow stages. Cumulative thickness of reservoir and fracture spacing affect EUR in the stage 2 to 5 of the flow. SRV radius (volume) and horizontal segment length affect EUR during stage 1 to 4 of the flow. Secondly, based on AHP, establish a shale gas EUR influencing factors evaluation model. We found that the key determining parameters for EUR after shale gas fracturing are SRV radius (volume), horizontal section length, and the number of fractures. Combined with the data of production wells, the production system is optimized and suggestions for improvement of poor wells are put forward. In engineering, the SRV radius (volume) of wells A_2 and A_3 can be extended from the stage 3 to 4 of the flow, and the length of horizontal section of well A_2 and the number of fractures of well A_3 can be increased in the stage 1 and 2 of the flow, reducing fracture spacing in well A_3 to improve EUR during the flow stage 5. Reducing the gas production rate in the 4th flow stage will increase the EUR of wells A_2 and A_3 in terms of production. Finality, there are still many deficiencies in the screening of influencing factors in this paper. During the case study, the production wells of a certain three new shale gas fields were selected, and the selection of wells and the acquisition of data were also based on the actual situation of the continental sedimentary gas field, which could not represent all similar gas wells. In future work, select appropriate methods and means and combine the research results and theoretical viewpoints in related fields to further optimize the parameters and weights to continuously improve the EUR evaluation level after shale gas fracturing.

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Authors Contributions
Jianxuan Jiang: Conception and design of the study. Jingguo Du: Conception and design of the study, Experiment, Writing an original draft, Analysis, and acquisition of data. Chaochen Ren: Conception and design of the study, Conduct molecular simulations, Writing an original draft, Analysis and acquisition of data. Yinhua Liu: Analysis and acquisition of data. Xincheng Gao: Analysis and acquisition of data. Long Li: Analysis and acquisition of data.

Availability of Data and Materials
Data is available on request from the authors. The data supporting this study's findings are available from the author (Jingguo Du), upon reasonable request.

Conflict of Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Y.C. Feng, C.Y. Ma, J.G. Deng, and et al. "A comprehensive review of ultralow-weight proppant technology.". *Petroleum Science*, **18**(3):20, 2021.

[2] J. Xie. "Practice of geology-engineering integration in Changning State Shale Gas Demonstration Area.". *China Petroleum Exploration*, **22**(1):21–28, 2017.

[3] X. Liang. "High-efficiency integrated shale gas development model of Zhaotong National Demonstration Zone and its practical enlightenment.". *China Petroleum Exploration*, **22**(1):29–37, 2017.

[4] T. Ran. "Geological features of shale gas accumulation in the Lower Silurian Longmaxi Formation, Southeast Chongqing.". *Petroleum Geology and Recovery Efficiency*, **24**(5):17–26, 2017.

[5] S. Du. "Permian shale gas reservoir characterization and favorable area identification in Junggar basin.". *Special Oil & Gas Reservoirs*, **25**(2):49–55, 2018.

[6] N. Liu and G. Wang. "Shale gas sweet spot identification and precise geo—steering drilling in Weiyuan Block of Sichuan Basin, SW China.". *Petroleum Exploration And Development*, **43**(6):978–985, 2016.

[7] X. Ma and J. Xie. "The progress and prospects of shale gas exploration and exploitation in southern Sichuan Basin, NW China.". *Petroleum Exploration and Development*, **45**(1):161–169, 2018.

[8] H. Song, Y. Su, X. Xiong, and et al. "EUR evaluation workflow and influence factors for shale gas well.". *Natural Gas Geoscience*, **30**(10):1531–1538, 2019.

[9] X. Xiong. "Quantitative evaluation of controlling factors on EUR of shale gas wells in Weiyuan block.". *China Petroleum Exploration*, **24**(4):532–538, 2019.

[10] Y. Su, G. Sheng, W. Wang, and et al. "A multi-media coupling flow model for shale gas reservoirs.". *Natural Gas Industry*, **36**(02):52–59, 2016.

[11] B. Faraj, H. Williams, G. Addison, and et al. "Gas potential of selected shale formations in the western Canadian sedimentary basin.". *Gas TIPS*, **10**(1):21–25, 2004.

[12] X. Zhang, J. Wu, X. Feng, and et al. "Numerical simulation of seepage flow characteristics of multi-stage fracturing (MSF) in horizontal shale gas wells.". *Natural Gas Industry*, **33**(3):47–52, 2013.

[13] H. Wang. "What factors control shale-gas production and production-decline trend in fractured systems: A comprehensive analysis and investigation.". *SPE Journal*, **22**:562–581, 2017.

[14] H. Wang and M. Matteo. "Impact of shale-gas apparent permeability on production: Combined effects of non-Darcy flow/gas slippage, desorption, and geomechanics.". *SPE Reservoir Evaluation & Engineering*, **18**:495–507, 2015.

[15] B. Xu, M. Haghighi, D. Cooke, and et al. "Production data analysis in Eagle Ford Shale Gas Reservoir.". *SPE/EAGE European Unconventional Resources Conference and Exhibition, Vienna, Austria.*, , 2012.

[16] J. Rushing, P. Alan, D. Albert, and et al. "Estimating reserves in tight gas sands at HP/HT reservoir conditions: Use and misuse of an Arps decline curve methodology.". *SPE Annual Technical Conference and Exhibition, Anaheim, California, USA.*, , 2007.

[17] Q. Zhang. "Study of productivity prediction method for horizontal wells in shale gas reservoir.". *China University of Petroleum (East China).*, , 2014.

[18] B. Chang, X. Qiang, Y. Yang, and et al. "Well testing curves of fractured horizontal wells in low-permeability gas reservoirs: characteristics and influencing factors.". *Well Testing*, **27**(02):1–6, 2018.

[19] Z. Wu. "Pressure behavior analysis of volume fracturing in horizontal wells in fractured tight oil reservoirs.". *Xinjiang Petroleum Geology*, **39**(3):333–339, 2018.

[20] X. Liu, X. Yang, Y. Chen, and et al. “Seepage behavior and well testing in horizontal shale gas wells under multi-stage fracking.”. *Natural Gas Industry*, **33**(12): 77–81, 2013.

[21] L. Cao. “Research on unsteady percolation theory and rate transient analysis in tight gas reservoirs.”. *Southwest Petroleum University.*, , 2017.

[22] L. Cao, L. Lu, X. Li, and et al. “A composite transient model for multi-fractured horizontal well in tight gas reservoirs based on multi-Factor effect.”. *SPE Europe featured at 80th EAGE Conference and Exhibition, Copenhagen, Denmark.*, , 2018.

[23] T. Yu. “Study on applicable conditions of linear flow model for staged fracturing horizontal wells.”. *Southwest Petroleum University.*, , 2016.

[24] X. Na, H. Yin, X. Li, and et al. “Analysis on influencing factors of pressure transient curves of multi-fracturing horizontal wells.”. *Contemporary Chemical Industry*, **47**(02):298–301, 2018.

[25] D. Xiao, WX. Chen, H. Deng, and et al. “Flaky cuttings bed distribution model in a shale gas horizontal well based on experiment and numerical simulation.”. *Energy Exploration & Exploitation*, **41**(1):104–135, 2023.

[26] RH. Krcek, K. Aminian, and A. Samuel. “The impact of stimulation treatment on EUR of devonian formations in the appalachian basin.”. *SPE Eastern Regional Meeting, Charleston, West Virginia, USA.*, , 2009.

[27] W. Liu. “Analysis of influencing factors of EUR in Bakken tight reservoir in the United States.”. *Petroleum Geology And Engineering*, **30**(2):139–141, 2016.

[28] R. Jiang, W. Teng, and J. Xu. “Transient pressure and production analysis methods for composite shale gas reservoirs stimulated by fracturing.”. *Natural Gas Industry*, **35**(9):42–47, 2015.

[29] H. Al, A. Hasan, A. Almarzooq, and et al. “CApplication of linear flow analysis to shale gas wells-field cases.”. *SPE Unconventional Gas Conference, Pittsburgh, Pennsylvania, USA.*, , 2010.

[30] C. Li, W. Gong, R. Zhang, and et al. “A calculation method of point source Solutions for performance of horizontal wells in edge-water gas reservoirs.”. *Natural Gas Industry*, **27**(7):89–91, 2007.

[31] L. Cinco, Heber, V. Samaniego, and et al. “Transient Pressure Behavior for a Well With a Finite-Conductivity Vertical Fracture.”. *SPE Journal.*, **18** (1978):253–264, 1978.

[32] Lee and Brockenbrough. “A New Approximate Analytic Solution for Finite Conductivity Vertical Fractures.”. *SPE 12013: Formation Evaluation 1988*, **1** (01):75–88, 1988.

[33] F. Medeiros, E. Ozkan, and H. Kazemi. “Productivity and Drainage Area of Fractured Horizontal Wells in Tight Gas Reservoirs.”. *SPE Reservoir Evaluation & Engineering*, **11**(05):902–911, 2008.

[34] Q. Zhu. “Study on production decline of multi-stage fractured horizontal wells in shale gas reservoirs.”. *Southwest Petroleum University.*, , 2015.

[35] W. Xie, Y. Zhu, S. Liu, and et al. “Two-phase seepage law and flowback evaluation of shale gas horizontal wells.”. *Natural Gas Industry*, **42**(S1):51–59, 2022.

[36] W. Liu, C. Qiao, P. Wang, and et al. “TStudy on fracture characteristics difference between fracturing fluid flowback and gas production stages of shale gas wells.”. *Chinese Journal of Theoretical and Applied Mechanics*, **55**(6):1–12, 2023.

[37] M. Zhang. “Study on influencing factors of volumetric fracturing productivity of shale gas reservoir.”. *Southwest Petroleum University.*, , 2016.

[38] Y. Liu. “Evaluation of horizontal well productivity in shale gas reservoirs.”. *Northeast Petroleum University.*, , 2018.

[39] R. Jiang, X. Liu, Y. Chui, and et al. “Bottom hole pressure analysis of multistage fractured horizontal well during unsteady crossflow.”. *Petroleum Geology and Recovery Efficiency*, **26**(05):86–95, 2019.

[40] Z. Wang, L. Zhang, R. Zhang, and et al. “Flow Mechanism and Transient Pressure Analysis of Multi-Stage Fractured Horizontal Well.”. *Chemistry and Technology of Fuels and Oils*, **57**:941–945, 2022.

[41] M. Chun, S. Junfeng, C. Guangzhi, and et al. “Study on Seepage Characteristics and Capacity Evaluation of Shale Gas Reservoirs.”. *Chemistry and Technology of Fuels and Oils*, **59**:1290–1303, 2024.

[42] Y. Cho, OG. Apaydin, and E. Ozkan. “Pressure-dependent natural fracture permeability in shale and its effect on shale gas well production.”. *SPE Reservoir Evaluation & Engineering*, **16**:216–228, 2013.

[43] Y. Chen, J. Zhou, J. Fan, and et al. “Study on productivity calculation method of horizontal well with volume fracturing in shale gas reservoir.”. *Journal of Yangtze University (Natural Science Edition)*, **20**(3), 2023.

[44] G. Han. “The seepage mechanism and productivity analysis in tight gas reservoir.”. *China University of Petroleum (East China).*, , 2016.

[45] L. Mu. “Numerical simulation of fractured horizontal well in tight low permeability gas reservoir.”. *Oil Drilling & Production Technology*, **32**(S1):127–129, 2010.

[46] M. Wei, H. Wang, Y. Duan, and et al. "Production profile prediction model of fractured marine-terrestrial transitional facies shale gas horizontal wells considering SRV heterogeneity between different sections.". *Natural Gas Industry*, **43**(8):80–89, 2023.

[47] TL. Saaty. "A Scaling Method for Priorities in Hierarchical Structures.". *Journal of Mathematical Psychology*, **15**(3):234–281, 1977.

[48] TL. Saaty. "Axiomatic Foundation of The Analytic Hierarchy Process.". *Management Science*, **32**(7):841–855, 1986.

[49] Y. Xu. "Comprehensive evaluation and production optimization of dewatering gas production technology on the tight gas production well.". *China University of Petroleum (East China).*, , 2018.