Production Capacity Evaluation of Horizontal Shale Gas Wells in Fuling District

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Abstract: One of the important indicators of shale gas reservoir excavation is capacity evaluation, which directly affects whether large-scale shale gas reservoirs can be excavated. Capacity evaluation is the basis of system analysis and dynamic prediction. Therefore, it is particularly important to conduct capacity evaluation studies on shale gas horizontal wells. In order to accurately evaluate the horizontal well productivity of shale gas staged fracturing, this paper uses a new method to evaluate the productivity of Fuling shale gas. The new method is aimed at the dynamic difference of horizontal wells and effectively analyzes the massive data, which are factors affecting the productivity of shale gas horizontal wells. According to the pressure system, production dynamic characteristics, well trajectory position, fracturing transformation mode and penetration depth, 32 wells were divided into four types. Then, based on the classification, the principal component analysis methods can be used to evaluate the horizontal well productivity of shale gas. The new method of capacity evaluation has improved the accuracy by 10.25% compared with the traditional method, which provides a theoretical basis for guiding the efficient development of the horizontal wells of Fuling shale gas.

Keywords: Fuling block, shale gas horizontal well, productivity analysis, classification, principal component analysis.

1 Introduction

With the reform of China's energy structure and the increasing demand for natural gas, shale gas as a clean energy has become an important supplement to promote sustainable social development. In 2012, the Ministry of Land and Resources completed the nation's first shale gas resource potential evaluation. The results show that China's shale gas recoverable resources are 25 trillion cubic meters [Zhang (2013)]. China's rich organic shale is very developed, with wide shale distribution, large stratum thickness and high organic carbon content [Zou, Dong, Yang et al. (2011)]. The maturity is moderate, which is conducive to shale gas accumulation and has great development potential [Zhang, Xu, Nie et al. (2008)]. At present, China's oil and gas field production process has fully realized informationization and automation, and more and more new data will emerge in oil and gas production, including various types of data such as operations, ground engineering production, and oil recovery [Sun (2018)]. Massive data analysis technology has been

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widely used in oil and gas production and development, and has shown great value [Hou, Li and Wang (2018)]. The development of "Global Data Information System Based on Big Data" by PetroChina Economic and Technological Research Institute has greatly improved the utilization of information resources and further improved the ability and level of competitive intelligence work [Lin, Zhou, Dai et al. (2019)].

In order to achieve better economic results in shale gas development, it is very important to further carry out research on shale gas production capacity evaluation methods. Cheng et al. [Cheng, Wang, Dong et al. (2009)], Wang et al. [Wang, Chen, Dong et al. (2009)], Li et al. [Li, Liu, Xiao et al. (2016)], and Hu et al. [Hu, Deng and Hu (2014)] all proposed to generate reservoir geological conditions as productivity evaluation methods. Ren et al. [Ren, Dou, Liu et al. (2012)], Xiao et al. [Xiao, Ning, Yang et al. (2015)], and Wu et al. [Wu, Liang, Bai et al. (2015)] proposed a capacity evaluation method based on the conditions of accumulation and taking into consideration development conditions. Li et al. [Li, Gao, Hua et al. (2014)], Li et al. [Li and Yang (2011)], Fan et al. [Fan, Shi and Pang (2011)], Guo et al. [Guo, Chen, Zhang et al. (2015)] proposed a comprehensive evaluation method which includes geological conditions, development utilization conditions, economic benefits and environmental factors.

In order to accurately evaluate the horizontal well productivity of shale gas staged fracturing, this paper uses a new method to evaluate the productivity of Fuling shale gas. The new method is aimed at the dynamic difference of horizontal wells and effectively analyzes the massive data, which are factors affecting the productivity of shale gas horizontal wells. According to the pressure system, production dynamic characteristics, well trajectory position, fracturing transformation mode and penetration depth, 32 wells were divided into four types. The new method of capacity evaluation has improved the accuracy by 10.25% compared with the traditional method, which provides a theoretical basis for guiding the efficient development of the horizontal wells of Fuling shale gas.

2 Horizontal well classification method

The potential of shale gas resources in Fuling block is huge, but due to low resource abundance, dense reservoirs and strong heterogeneity, there are huge geological risks in the development of shale gas, which makes it difficult for such projects to achieve commercial development [You (2017)]. According to the geological characteristics of the Fuling block, the first phase of production and construction areas are divided into the main area, the western area, the eastern area and the southwest area.

The water production and gas production in different regions show complexity. Therefore, the evaluation method requires dynamic analysis of existing data, single wells, well groups, blocks, etc., and research and optimization of massive data. By sorting data from wells produced in 32 ports, the gas production, water production, gas-water ratio, and pressure variation characteristics of each well were classified and counted. Conduct a correct, objective, and scientific comprehensive evaluation of shale gas development results to guide the next development and adjustment.
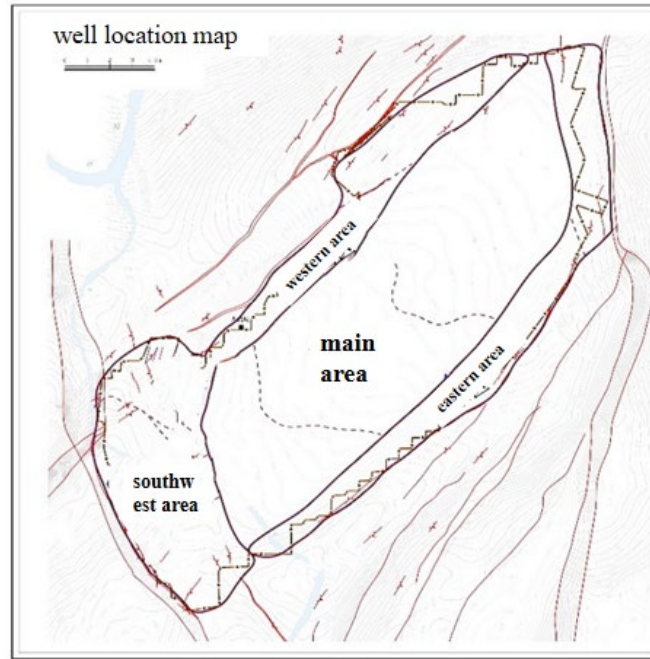
Figure 1: Comprehensive partition map of the first phase of production and construction areas

In order to make the index system scientific and standardized, it is possible to accurately evaluate the production capacity of shale gas horizontal well, the following principles should be followed:

(1) Classification according to pressure system. ① Production and construction areas are divided into four types: the main area, the western area, the eastern area and the southwest area. ② According to the trend of casing pressure change can be divided into three categories: sleeve pressure drop type, sleeve pressure stable type, sleeve pressure basic stable type. ③ According to the relationship between casing pressure and gas production, there are two categories: If the relationship between the casing pressure and the gas production is consistent, this type is called the consistency between the casing pressure and the gas production; If the relationship between the casing pressure and the gas production is inconsistent, it is called the inconsistency between the casing pressure and the gas production.

(2) According to the shale gas horizontal well production dynamic characteristics classification: ① According to the gas production change characteristics are divided into three categories: Gas production change without stability stage, stable stage gas production less than $4\times10^4\,\text{m}^3/\text{d}$, stable stage gas production is greater than $4\times10^4\,\text{m}^3/\text{d}$. ② According to the characteristics of water production changes are divided into two categories: larger water production (>4000 m³), smaller water production (<4000 m³).

(3) According to the position of the wellbore trajectory, it is divided into three categories: located in the upper part of the reservoir, in the middle of the reservoir, and in the lower part of the reservoir.

(4) According to the horizontal depth of the horizontal well, it is divided into four types: low penetration depth (<1500 m), low penetration depth (1500 m-2000 m), medium penetration depth (2000 m-2600 m), and high penetration depth (2600 m-3000 m).

(5) According to the fracturing transformation mode, it is divided into two categories: high fracture pressure (>70 MPa) and low fracture pressure (<70 MPa).

According to the above classification principle, 32 horizontal wells of Fuling shale gas were classified and evaluated, which were mainly divided into four types of wells.

2.1 Class I production wells

There are 12 wells in Class I wells, mainly located in the western part of the block. The production dynamics are poor, the production process is unstable, the gas well production is unstable. There is no stable production stage, the well is intermittently opened, the fracture pressure is high, and the casing pressure drops when the gas production decreases. The permeability is low and the water production is generally large.
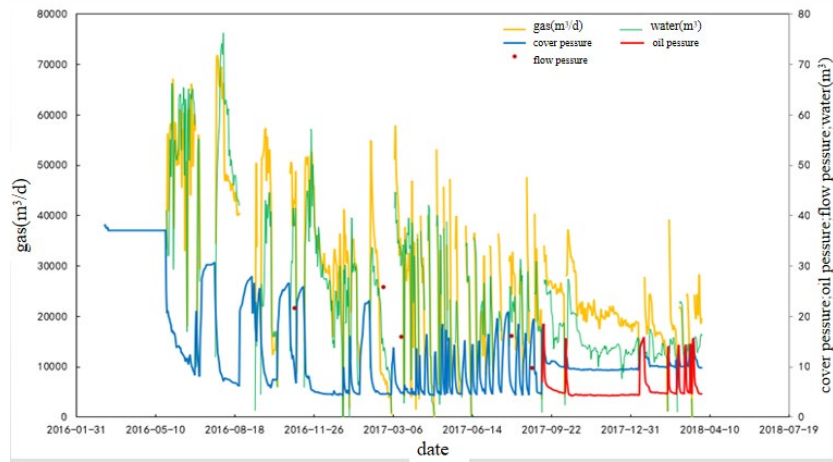
Figure 2: Dynamic characteristics of production wells in Class I wells

2.2 Class II production wells

There are 5 types of wells in Class II wells, which are located in the middle of the structure and have a stable production stage. The casing pressure and gas production are in a stable and decreasing relationship. The reasonable working system corresponds to the steady decline of gas production and pressure. The matrix has a high permeability, the depth does not exceed 3,000 meters, and the water production is small.
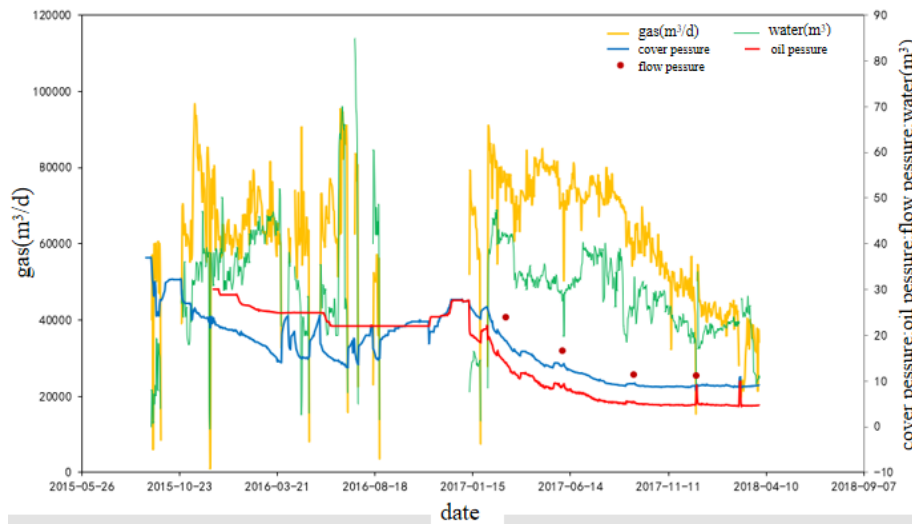
Figure 3: Dynamic characteristics of production wells in Class II wells

2.3 Class III production wells

There are three types of wells in Class III wells, which are located at the edge of the structure. The production process is relatively stable, the gas production is reduced, and the casing pressure is basically stable. The fracture fracturing is high, the number of perforation clusters is large, the matrix permeability is low, and the well trajectory is located in the middle of the reservoir. The production of single well is basically unchanged, and the gas production in the stable stage is less than 4×10^4 m^3/d, and the water production is large.
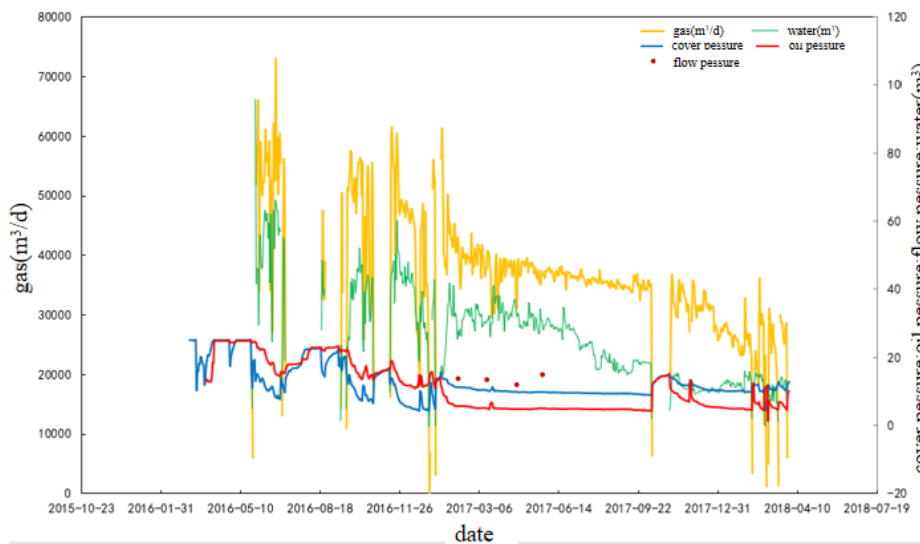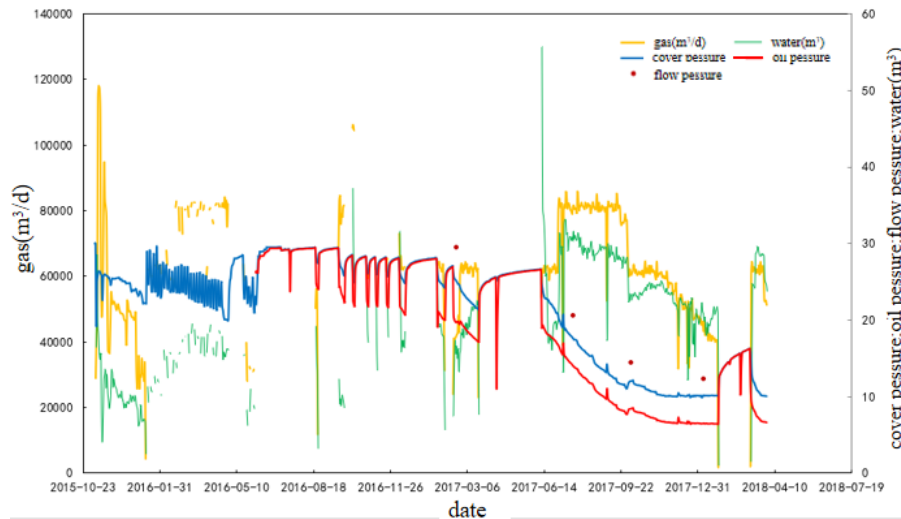

Figure 4: Dynamic characteristics of production wells in Class III wells

2.4 Class IV production wells

There are 12 types of wells in Class IV wells, mainly located in the eastern part of the block. There is a stable production stage in this type of well, and the casing pressure drops when the gas volume is stable. The overall pressure of the casing is kept high and the water production is small. This type of well has a high matrix permeability and a depth of approximately 2,500 meters.

Figure 5: Dynamic characteristics of production wells in Class IV wells

3 New methods for capacity evaluation

3.1 Classification results

According to the classification principle, the productivity evaluation of Class I wells, Class II wells Class III wells and Class IV wells were carried out. The statistical results for the four types of wells are as follows:

Table 1: Analysis of classification results of four types of wells

Category	Quantity (port)	Area	Pressure system	Production dynamic characteristics	Wellbore trajectory position	Fracturing transformation mode	Threading depth
Class I wells	12	West area	Type of pressure drop	No stable phase type of gas production change	Upper part of the reservoir	Type of high burst pressure	Type of lower penetration depth
Class II wells	5	Main area	Nested stable type; The casing pressure is consistent with the change in gas production	Gas production in the stable stage is less than 4×10^4 m³/d	Central part of the reservoir	Type of high burst pressure	Type of higher penetration depth

| Class III wells | 3 | Southwest area | Type of pressure drop | Gas production in the stable stage is less than 4×10^4 m³/d | Lower part of the reservoir | Type of high burst pressure | Type of lower penetration depth |
| Class IV wells | 12 | Eastern area | Nested stable type; The casing pressure is consistent with the change in gas production | Gas production in the stable stage is more than 4×10^4 m³/d | Lower part of the reservoir | Type of low burst pressure | Type of middle penetration depth |

3.2 Principal component analysis

According to a large number of data filtering, this paper selected 19 influencing factors and conducted principal component analysis [Sun, Liu and Dong (2016)] for production capacity evaluation. The specific steps are as follows: ① standardize the data; ② perform principal component analysis, reduce the multiple indicators into a few comprehensive indicators through dimensionality reduction; ③ find the feature vector and principal component; ④ linear regression; ⑤ verify and map; ⑥ calculate the scores and rankings of each factor.

Let X (factors affecting the production of shale gas horizontal wells include: horizontal length X_1, number of fracturing segments X_2, cutting density X_3, original gas layer pressure X_4, DEN X_5, TOC X_6, porosity X_7, matrix Permeability X_8, gas content X_9, brittleness index X_{10}, perforation cluster number X_{11}, burst pressure X_{12}, construction pressure X_{13}, pump stop pressure X_{14}, construction displacement X_{15}, total liquid volume X_{16}, total sand amount X_{17}, average sand ratio X_{18}, target reservoir thickness X_{19}) be a random variable of Y. (actual initial capacity value)

$$X = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_{19} \end{pmatrix} \tag{1}$$

Standardize the 19 influencing factors to obtain a standardized matrix:

$$ZX_i = \frac{X_i - \overline{X_i}}{\sigma_{Xi}} \tag{2}$$

where ZX_i is X_i's standardized variable, X_i is the i-th influencing factor, $\overline{X_i}$ is the average value of X_i and σ_{Xi} is the standard deviation of X_i.

Put the factor of the eigenvalue. If the two feature values are worth more than 90%, the third principal component can be removed to obtain the corresponding factor load matrix (i.e., the component matrix).

Find the eigenvector and the principal component. Because there are different eigenvalues for different selections, only the first two eigenvalues are explained. Others

are similar. The standard orthogonalized eigenvectors corresponding to the first two eigenvalues λ1 λ2 are:

$$\varphi_1 = \left(\frac{\text{Component matrix}(Z_{11})}{\sqrt{\lambda_1}}, \frac{\text{Component matrix}(Z_{21})}{\sqrt{\lambda_1}}, \frac{\text{Component matrix}(Z_{31})}{\sqrt{\lambda_1}} \right) \tag{3}$$

$$\varphi_2 = \left(\frac{\text{Component matrix}(Z_{12})}{\sqrt{\lambda_2}}, \frac{\text{Component matrix}(Z_{22})}{\sqrt{\lambda_2}}, \frac{\text{Component matrix}(Z_{32})}{\sqrt{\lambda_2}} \right) \tag{4}$$

A least squares regression analysis of the principal component dependent variable Y is performed on the principal component. Then restore the relationship to the original variable according to the following two formulas.

$$x = ZX\sigma x + \overline{x} \tag{5}$$

$$y = ZX\sigma y + \overline{y} \tag{6}$$

3.3 Example comparison analysis results

On the basis of classification, a class of well data corresponding to X_1, X_2, X_3, ..., X_{19}, Y_1 are substituted into formulas (1), (2), (3), (4), (5), (6). A ranking of factors affecting wells (Tab. 2).

Table 2: Ranking factors affecting the Class I wells by principal component analysis (take the top five)

Overall ratings	Indicator name	Ranking
0.359511	Matrix permeability (nd) X_8	1
0.349984	Number of fracturing segments X_2	2
0.326469	Construction pressure (MPa) (maximum) X_{13}	3
0.299548	Total liquid volume (m³) X_{16}	4
0.288805	Total sand amount (m³) X_{17}	5

It can be seen from the table that the main factors affecting Class I wells are matrix permeability, number of fracturing sections, construction pressure, total liquid volume and total sand volume. When developing unstable wells, we should pay attention to controlling the above factors, so that we can develop horizontal wells more economically and effectively.

Do a regression analysis of the least squares of the dependent variable X. Calculate the regression coefficient and derive the estimated value by the regression coefficient [Sun, Liu and Dong (2016)]. Restore back to the original variable and get the capacity prediction equation as follows:

$$Y = 0.01 \times X_1 - 0.03 \times X_2 - 2.46 \times X_3 - 0.04 \times X_4 + 3.25 \times X_5 + 0.63 \times X_6$$
$$- 2.14 \times X_7 - 0.01 \times X_8 + 0.06 \times X_9 - 0.01 \times X_{10} + 0.03 \times X_{11} - 0.05 \times X_{12}$$
$$+ 0.12 \times X_{13} + 0.17 \times X_{14} + 0.07 \times X_{15} - 0.00001 \times X_{16} + 0.0007 \times X_{17} + 0.97 \times X_{18} - 0.26 \times X_{19}$$

where X_1 is the horizontal length, X_2 is the number of fracturing segments, X_3 is the cutting density, X_4 is the original gas layer pressure, X_5 is the DEN, X_6 is the TOC, X_7 is the porosity, X_8 is the matrix Permeability, X_9 is the gas content, X_{10} is the brittleness index, X_{11} is the perforation cluster number, X_{12} is the burst pressure, X_{13} is the construction pressure, X_{14} is the pump stop pressure, X_{15} is the construction displacement , X_{16} is the total liquid volume, X_{17} is the total sand amount, X_{18} is the average sand ratio and X_{19} is the target reservoir thickness.

Table 3: Class I wells comparison of the calculated value of the regression formula with the actual value

Well number	Original value	Regression formula calculation	Difference
JY X-1HF	3.19	7.17	-3.98
JY X-2HF	7.42	5.19	2.23
JY X-3HF	13.75	12.85	0.90
JY X-4HF	5.99	7.29	-1.30
JY X-5HF	6.08	5.78	0.30
JY X-6HF	13.59	11.51	2.08
JY X-7HF	14.24	14.63	-0.39
JY X-8HF	11.83	8.74	3.09
JY X-9HF	4.29	8.59	-4.30
JY X-10HF	7.80	4.14	3.66
JY X-11HF	5.12	5.03	0.09
JY X-12HF	2.22	4.59	-2.37

(Note: HF refers to horizontal well fracturing, which is the abbreviation of Horizontal Well and Fractured.)
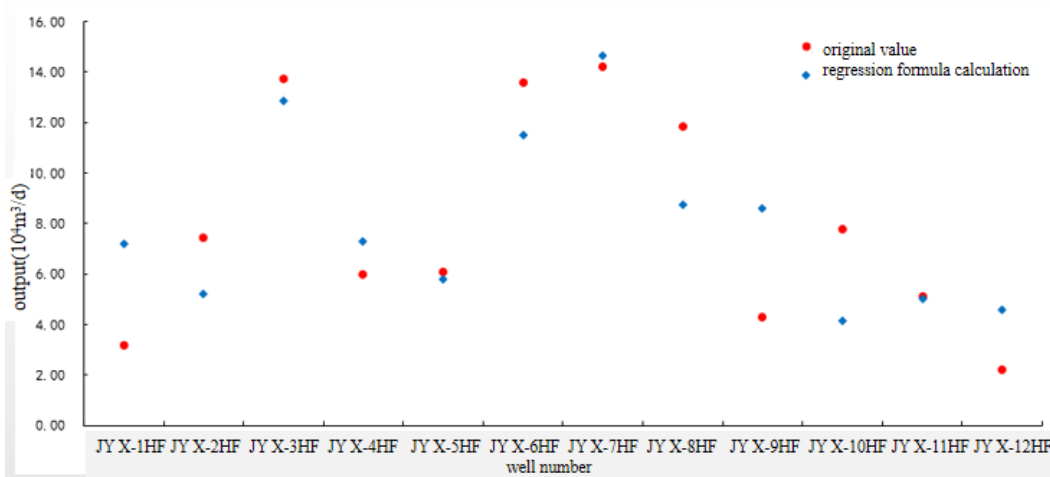
Figure 6: Comparison of the actual initial production capacity value of the Class I wells and the calculated value of the regression formula

Table 4: Comparison of calculated and actual values of integrated regression formula for class I and class II wells not classified

Well number	Original value	Regression formula calculation	Difference
JY X-1HF	3.19	11.08	-7.90
JY X-2HF	7.42	6.42	0.995
JY X-3HF	13.75	2.96	10.79
JY X-4HF	5.99	16.56	-10.57
JY X-5HF	6.08	20.17	-14.10
JY X-6HF	13.59	24.82	-11.23
JY X-7HF	14.24	24.75	-10.51
JY X-8HF	11.83	10.41	1.42
JY X-9HF	4.29	18.49	-14.20
JY X-10HF	7.8	15.81	-8.005
JY X-11HF	5.12	4.09	1.03
JY X-12HF	2.22	-1.12	3.337
JY Y-1HF	48.04	32.03	16.009
JY Y-2HF	35.91	29.17	6.74
JY Y-3HF	52.72	41.65	11.07
JY Y-4HF	26.51	10.26	16.25
JY Y-5HF	18.33	9.47	8.86

(Note: HF refers to horizontal well fracturing, which is the abbreviation of Horizontal Well and Fractured.)

Comparing the actual initial production capacity value of a class of wells with the value calculated by the regression formula can control the difference to within 5%-50%, showing

a good consistency [Sun, Liu and Dong (2016)]. In order to show the necessity and accuracy of the classification, the principal component analysis method is also used to integrate the Class I wells with the Class II wells and then compare the actual initial productivity with the regression formula.
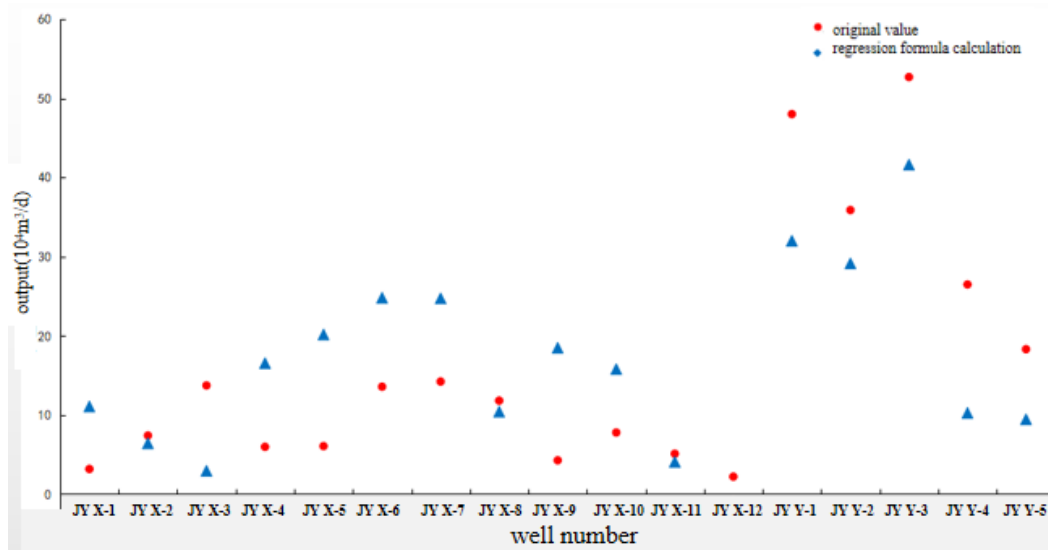
Figure 7: Comparison of actual initial productivity values and regression formulas for class I and class II wells not classified

As shown in Fig. 7, when the class I and class II wells are not classified, the obtained capacity prediction results and the actual initial capacity difference values are larger. After classifying the wells, Class I wells show better consistency. The difference between Fig. 6 and Fig. 7, which is equivalent to the difference between classification (Fig. 6) and no classification (Fig. 7). The values in the two figures are compared, and the average value is calculated using mathematics to obtain 10.25%. It is feasible and necessary to identify the new method of shale gas horizontal well. It is recommended that the method be applied to the shale gas well productivity evaluation analysis to evaluate the correct and objective page. The production capacity of horizontal gas wells guides the next step of efficient development of shale gas wells.

4 Conclusions

(1) According to the five principles of pressure system, production dynamic characteristics, well trajectory position, fracturing transformation mode and penetration depth, 32 wells of Fuling shale gas can be divided into four categories.

(2) On the basis of classification, the principal component analysis method is used to carry out the classification productivity evaluation, and the actual initial production capacity value is compared with the value calculated by the regression formula, and the difference can be controlled within 5%-50%, shows good and consistent.

(3) By comparing the pre- and post-classification capacity prediction results with the actual initial production capacity, the accuracy is improved by 10.25%. It is concluded that the new method of capacity evaluation has higher accuracy. It is recommended that this method be applied to the shale gas well productivity evaluation analysis. The method can evaluate the correct and objective production capacity of shale gas horizontal wells. Guide the next high-efficiency development of shale gas wells.

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