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Research Article

Optimization of shale-gas horizontal well spacing based on geology–engineering–economy integration: A case study of Well Block Ning 209 in the National Shale Gas Development Demonstration Area[☆,☆☆]

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Abstract

In order to maximize the resource utilization rate, it is common to adopt one-time overall deployment of well pattern to develop shale gas, and the design of horizontal well spacing is the key to the deployment of shale gas well pattern. To determine the optimal well spacing, it is not only necessary to understand both geological characteristics and drilling fracturing technology, but also take into consideration the influences of economic factors, such as gas price and cost. At present, there is no reliable method for designing the well spacing of shale-gas horizontal wells at home and abroad. In this paper, a method for analyzing the well spacing of shale-gas horizontal wells based on the integration of geology, engineering and economy was established for the first time. Then, by means of geological modeling, numerical simulation and cash flow analysis, the well spacing of shale-gas development wells in Well Block Ning 209 in the Changning–Weiyuan National Shale Gas Demonstration Area in the Sichuan Basin was comprehensively evaluated by using estimated ultimate reserve (EUR), recovery factor and internal rate of return (IRR). And the following research results were obtained. First, under the current geological, engineering and economic conditions of Well Block Ning 209, the IRR of shale gas platform development can be kept greater than 8% if the well spacing is larger than 240 m. Second, when the well spacing is controlled between 330 m and 380 m, single well EUR, recovery rate of the platform and economic benefit can be considered simultaneously. In conclusion, the research results support the formulation of the shale gas development technology policy of Well Block Ning 209 and lay a foundation for the realization of its scale efficient development of shale gas.

Keywords: Shale gas; Reasonable well spacing; Well interference; Geological modeling; Numerical simulation; Integration; Workflow; Economic benefit; Well block Ning 209

0. Introduction

Shale gas reservoirs can only be effectively developed via the "horizontal well + volume fracturing" technique. After a horizontal section is fractured, a complex induced fracture network will be formed around the wellbore. However, it is difficult to accurately determine the reasonable well spacing between two horizontal wells due to the challenges of microseismic, tracing agent and other monitoring technologies in

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quantitatively characterizing fracture geometry and proppant distribution in fractures. Too large well spacing will cause the reserves between the wells not fully utilized, resulting in waste of resources, while too small well spacing will induce well interference, which may seriously affect the production effect of a gas well. There are relatively few studies on shale gas well spacing in China, but some experience has been accumulated in the development of shale gas in North America. Cakici et al. [1] carried out a dynamic monitoring test of variable well spacing within a well cluster in the Marcellus shale gas reservoir, and determined the effective extension distance of fracture. Lalehrokh et al. [2] studied the relationship between well spacing and net present value (*NPV*) in the Eagle Ford shale gas reservoirs by introducing an economic model. Kim et al. [3] combined the pressure characteristic curve with numerical simulation, and judged the occurrence time of well interference through well spacing sensitivity analysis. Orozco et al. [4] used the modified material balance equation (MBE) to calculate well spacing under the assumption that the gas discharge area of a horizontal well was rectangular. Pankaj et al. [5] evaluated the Marcellus shale gas well spacing by using the geology−engineering integration and numerical simulation. They believed that the optimal well spacing is about 300 m under the current fracturing process conditions, and proposed that well spacing is closely related to fracturing scale. Nonetheless, there is no unified idea on how to define the most reasonable well spacing around the world. Hence, the research in this regard is very necessary.

1. Occurrence of well interference in the Changning block

In the Changning block of the Changning−Weiyuan National Shale Gas Demonstration Area in the Sichuan Basin, nearly 200 wells have been put into production. The production effects have been constantly improved, and the main producing layer is the Upper Ordovician Wufeng Formation−Lower Silurian Longmaxi Formation shale [6]. With the adjustment of the development well spacing, well interference is common during the fracturing and production of different batches of horizontal wells, which has impact on the development effects of new and old wells. As shown in Fig. 1, during 2014−2019, the well spacing of shale gas horizontal wells in the Changning block was reduced from 500−600 m to 300−400 m, and the probability of well interference gradually increased; especially in 2017, the dominant well spacing was smaller than 400 m, and the well interference was more obvious.

According to North American shale gas development experience, well interference is caused by the interconnection of hydraulic fractures between two wells. Such interconnection is attributable to many factors. The objective factors include reservoir heterogeneity, in-situ stress characteristics, and natural fractures development. The subjective factors include the horizontal well drilling horizon, fracturing scale and production sequence. In the Changning block, well interference mainly occurs in three cases: fracturing−production, fracturing−fracturing and fracturing−shut-in. Well interference in fracturing−production refers to the interference of production and pressure caused by the fracturing of shale gas wells to an adjacent well that was put into production earlier, mainly because a pressure drop funnel is formed around the adjacent well after production, which makes the fractures easier to extend to the low pressure zone [7]. Well interference in fracturing−fracturing and fracturing−shut-in refers to the channeling caused by fracturing fluids directly entering the induced fractures of the adjacent wells when the adjacent wells have no obvious earlier pressure drop.

Field three-dimensional seismic ant body tracking and wellhead pressure monitoring (Fig. 2) show that well interference dominantly takes place in a certain section or several sections, but not across the wellbore (Fig. 3). Although some obvious disturbances can be identified from the pressure and production data, it is more necessary to judge whether local well interference will affect the *EUR* of a gas well and the overall recovery factor of a well cluster. This is critical to the design of well spacing and also a focus in shale gas development around the world.

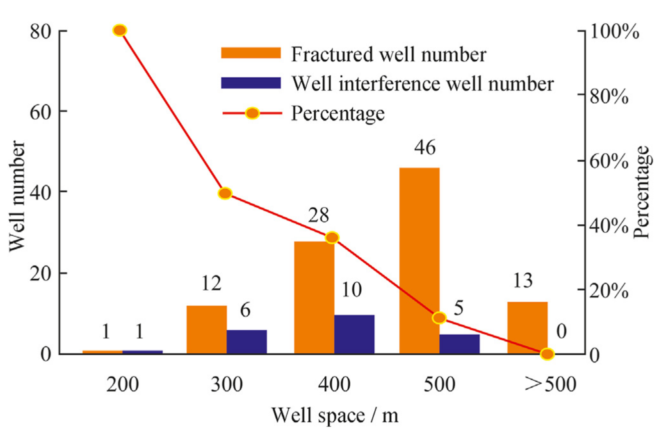

Fig. 1. Histogram of well interference at different well spacing in the Changning block.

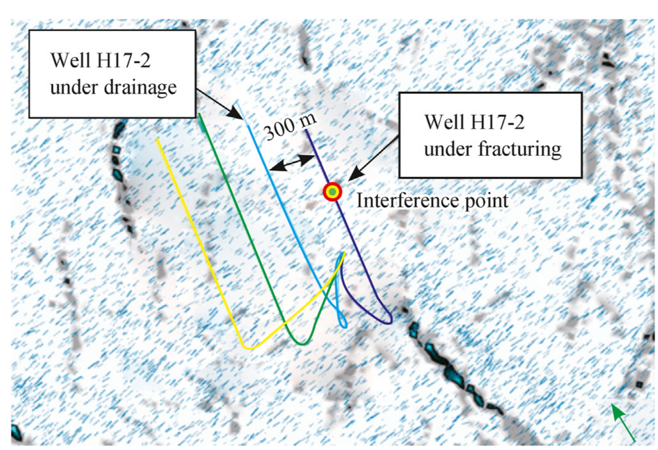

Fig. 2. Model of natural fracture prediction by ant tracking on the H17 platform of Well Block Ning 209.

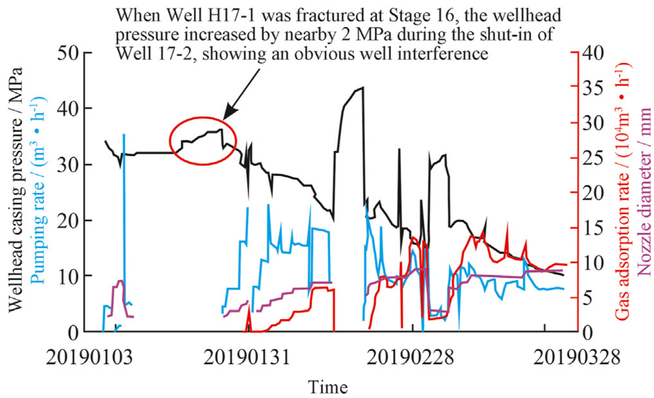

Fig. 3. Drainage curves of Well H17-2 in Well Block Ning 209.

2. Workflow of geology−engineering integration

As an unconventional resource, shale gas can only be developed extensively and beneficially with the support of geology−engineering integration, which generally requires multi-disciplinary and multi-professional coordination and multi-engineering technology collaboration for geological study, and is essentially to create a fine three-dimensional geological model [8].

In order to accurately evaluate the reasonable well spacing, it is necessary to establish a three-dimensional model that can objectively reflect the geological engineering characteristics of the block. On this basis, the actual fracturing process parameters are used to simulate the induced fracture network. Finally, a numerical model of multi-stage fracturing for shale gas horizontal wells is established. At present, the modeling and simulation software commonly used in the industry was developed by Schlumberger. The software can couple multiple information sources, such as geology, geophysics, rock mechanics, and gas reservoir engineering, and simulate well interference by reconstructing the pressure field and stress field changes during gas well production in a three-dimensional space [9,10]. In North America, some scholars have adopted a relatively fixed workflow to study the reasonable well spacing, including five steps: modeling, fracturing simulation, history matching of production performance, stress field update, and child-well fracturing simulation & productivity prediction (Fig. 4). The well spacing of the Haynesville gas field is optimized. For example, under different well spacing conditions, the influence of formation initial pressure drop after the parent well is put into production on the expansion of the fracture network of child wells can be considered [11,12].

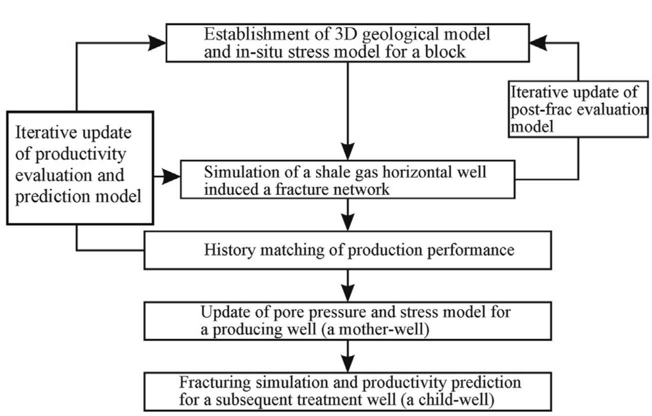

Fig. 4. Workflow of shale gas well spacing evaluation by geology−engineering integration in North America.

3. Economic benefit evaluation

3.1. Necessity of economic benefit evaluation

Compared with conventional gas, shale gas is characterized by rapid production decline and high production cost, so its final EUR forecast is uncertain. Some scholars have conducted relevant studies on shale gas development from the perspective of economic feasibility, and proposed that minimizing costs is fundamental for the sustainable development of shale gas [13,14]. Hence, it is necessary to conduct economic analysis to judge the reasonable well spacing and reduce the risk in shale gas development.

There are many small and medium oil companies engaged in shale gas development in North America. They mainly adopt the mode of progressive development with large well spacing in the early stage and denser well pattern in the later stage [15]. All shale gas development projects in North America follow the principle of “benefit foremost”, that is, they pursue the maximization of economic benefits together with the maximization of single-well EUR. Therefore, oil companies in North America will adjust the well pattern according to the acreage purchased or leased. In the early stage of development, large well spacing is used in large acreage; after one to four years of production of the mother-well, the wells are infilled according to gas price. In the Changning block, however, the geological engineering characteristics of shale reservoirs are different from those in North America [16,17], and one-time overall deployment of well pattern is mainly adopted. These objective conditions require operators to adopt a work principle of geology−engineering−economy integration depending on actual conditions, and use a variety of methods to comprehensively demonstrate the reasonable well spacing, so that the output, economic benefit and recovery factor can be balanced.

3.2. Economic evaluation parameters

The net present value (*NPV*) and internal rate of return (*IRR*) are two indicators Chinese companies use to evaluate whether an investment is economic. These two indicators can be used to judge the capital status of the project by considering the time value of capital, and can reflect the effectiveness and quality of the investment [18,19]. In this study, IRR is used to evaluate the economic benefits of gas well production under different well spacing. It is expressed as:

Table 1
Basic parameters of economic evaluation on shale gas development in Well Block Ning 209.

Economic parameter	Value
Surface construction engineering cost/CNY 10 thousand yuan	1000
Drilling cost/CNY 10 thousand yuan	1800
Fracturing cost/CNY 10 thousand yuan	2500
Shale gas lifting cost/CNY 10 thousand yuan per thousand m^3	200
Natural gas price/CNY 10 thousand yuan per thousand m^3	1275
Value-added tax rate	9%
Benchmark discount rate	8%

$$\sum_{t=0}^{n}(CI-CO)_t(1+IRR)^{-t}=0 \quad (1)$$

where, *IRR* represents the internal rate of return, that is, if *IRR* > the benchmark discount rate, the project is considered economic; similarly, *CI*: the cash inflow from a shale gas well in the evaluation period, RMB10^4; *CO*: the cash outflow from a shale gas well in the evaluation period, RMB10^4; *t*: the evaluation period, and t = 20 years (consistent with the cut-off time for single well *EUR* calculation) in this study.

The cash inflow consists of shale gas sales revenue. The cash outflow mainly includes investment (well drilling and completion, and surface engineering costs), production costs (operating costs, equipment depreciation, etc.), and corresponding taxes. The basic parameters of economic evaluation used in this study are shown in Table 1.

4. Case application

4.1. Basic information

Well Block Ning 209 is currently the main production area in the Changning block. In the target layer Wufeng Formation–Longmaxi Formation, Type I+II reservoirs are 32 to 36 m thick, with a burial depth of 3000–3500 m and a pressure coefficient of 1.8–2.0, indicative of over-pressure gas reservoirs. The minimum horizontal principal stress is between 71 and 73 MPa, and the average horizontal stress difference is 16.7 MPa. Natural fractures are relatively developed. The average fracturing length of treated horizontal wells are 1500 m, and the main fracturing parameters are shown in Table 2.

Table 2
Main geological and engineering characteristic parameters of Well Block Ning 209.

Item	Parameter	Value
Geological engineering	Porosity	5.1–6.3%
	Gas content/($m^3 \cdot t^{-1}$)	5.3–6.2
	TOC	3.2–3.6%
	Thickness of type I + II reservoirs/m	32–36
	Pressure coefficient	1.8–2.0
	Burial depth/m	3000–3500
	Minimum horizontal principal stress/MPa	71–73
	Horizontal stress difference/MPa	16.7
Fracturing technology	Length of horizontal section fractured/m	1500
	Stage spacing/m	60
	Number of clusters per stage	3
	Cluster spacing/m	20
	Sanding strength/($t \cdot m^{-1}$)	2.0–2.5
	Displacement/($m^3 \cdot min^{-1}$)	15–16

4.2. Modeling of platform well cluster

A three-dimensional model of Well Block Ning 209 platform was established in accordance with the "integration workflow", with a size of 1700 m × 1400 m × 30 m and reserve abundance of 5.17 × 10^8 m^3/km^2. A total of five well cluster schemes were designed, i.e. 2, 3, 4, 5, and 6 wells, to simulate the influence of well interference when the well spacing is 200–600 m (Fig. 5). The fracturing network simulation of horizontal wells adopts the average fracturing parameters of Well Block Ning 209, and all wells are put into production simultaneously after fracturing.

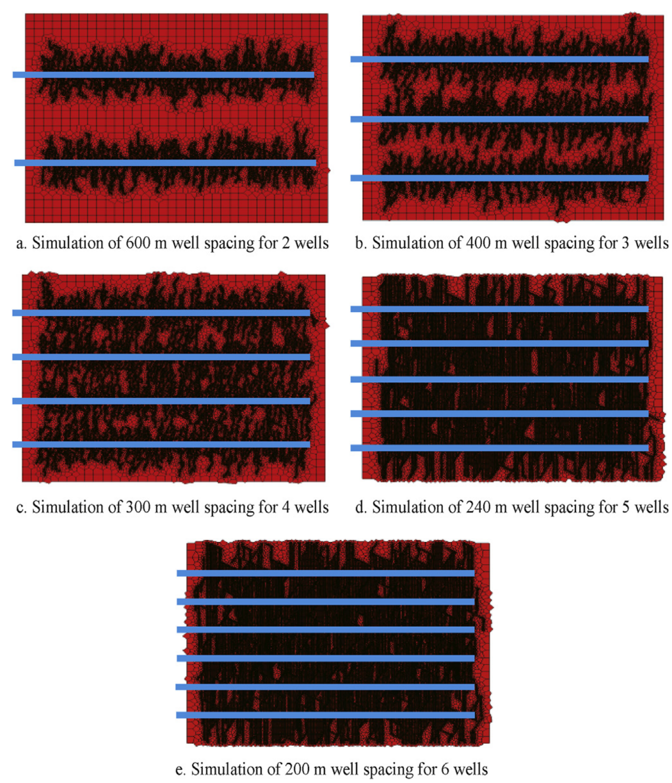

Fig. 5. Numerical model of geology–engineering integration for 2–6 wells.

4.3. Results

Fig. 6 shows the results of the average daily gas production and the *EUR* of the wells obtained by the simulation of the five schemes. With the reduction of well spacing, the degree of well interference increases, the daily gas production of shale

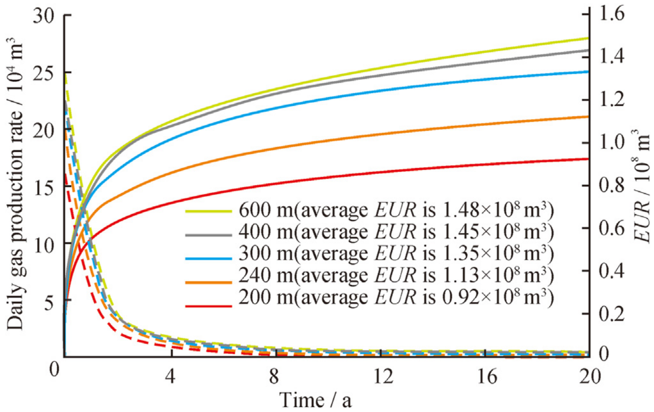

Fig. 6. Curves of average daily gas production and *EUR* of shale gas wells under different well spacing.

gas wells gradually deteriorates, and the *EUR* continues to decline. Since there are five wells in the platform model with the spacing of 200 m, the recovery factor is still relatively high. However, due to severe well interference, the gas recovery of the platform with a well spacing of 200 m for six wells is smaller than that of the platform with a well spacing of 240 m for five wells (Fig. 7).

Fig. 8 shows the predicted distribution of formation pore pressure after 20 years under different well spacing. When the well spacing is greater than 400 m, there are still remaining reserves between wells that have not been produced. When the well spacing is 300 m, most of the induced fractures are connected, but there are still areas where reserves are not fully recovered. When the well spacing is further reduced to below 240 m, the well interference becomes very serious, and the formation pressure within the well control range drops significantly, which indicates that the well-controlled reserves have basically been recovered.

By incorporating the *EUR* calculated under the five schemes into Formula (1), the IRR corresponding to 20 years of production for each scheme can be obtained through cash flow analysis. The calculation results are shown in Fig. 9. With the increase of well spacing, the number of wells that need to be drilled in the same platform

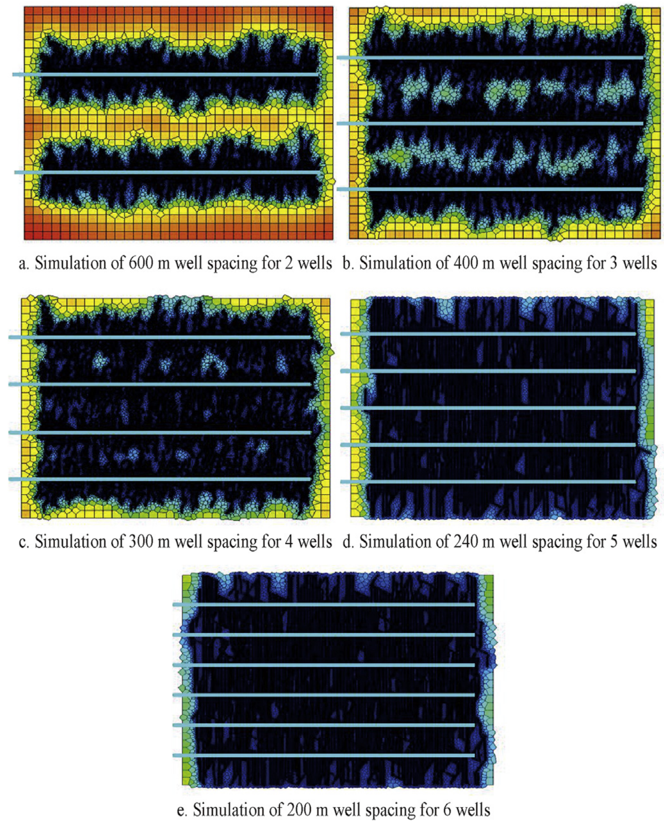

Fig. 8. Distribution of formation pore pressure in the shale gas platform after 20 years.

decreases, and the investment in drilling and completion also decreases accordingly. However, the IRR for platform production is greater. Compared with the platform of six wells, the platform with two wells have a lower recovery, but the investment is relatively lower, and the economic benefits are better. From the perspective of economic benefits, the well spacing is not as large as possible, but there is a critical value. Once the well spacing exceeds this critical value, the increase in IRR is not obvious. The critical well spacing calculated in this case is 380 m, and the corresponding IRR is 16.9%.

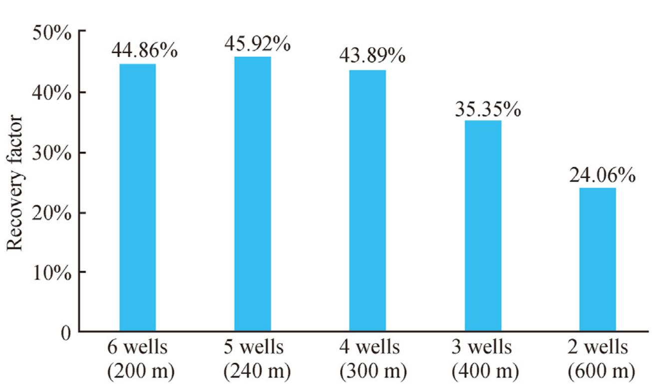

Fig. 7. Recovery factors of shale gas platform under different well spacing.

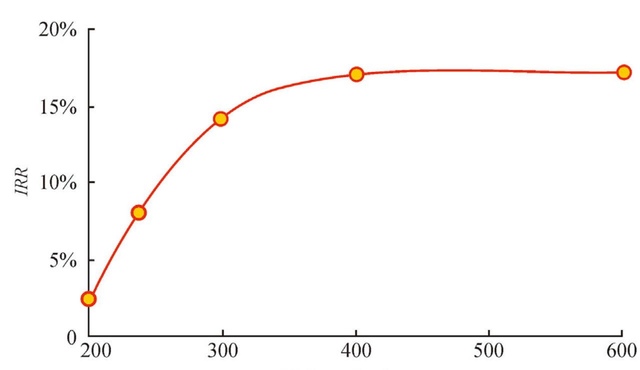

Fig. 9. Variation of IRR of the shale gas platform under different well spacing.

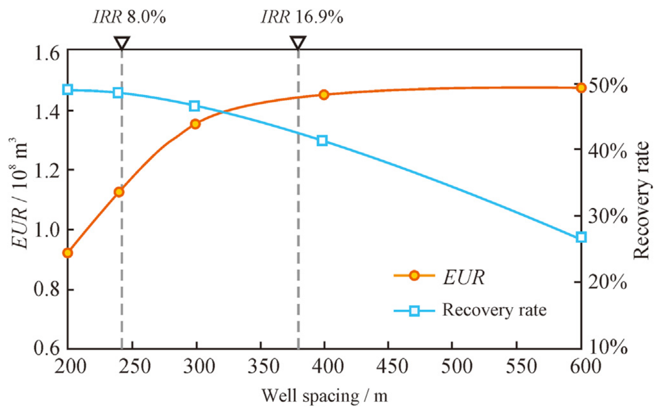

Fig. 10. Comprehensive analysis chart of the reasonable well spacing in Well Block Ning 209.

well spacing does not exceed the upper limit of the critical economic well spacing.

The shale gas well spacing research method based on "geology−engineering−economic integration" shows that there is no "unique optimal well spacing" in any shale gas reservoir. The change of geological characteristics, the optimization of technology and the continuous decrease of drilling and completion costs will lead to the change of optimum well spacing. According to the latest understanding of geological, technological and economic parameters, the acceptable range of shale gas well spacing can be demonstrated by adopting the idea of geology−engineering−economy integration (Fig. 11). Additionally, it is more reasonable to deploy a shale gas horizontal well platform according to the range of well spacing.

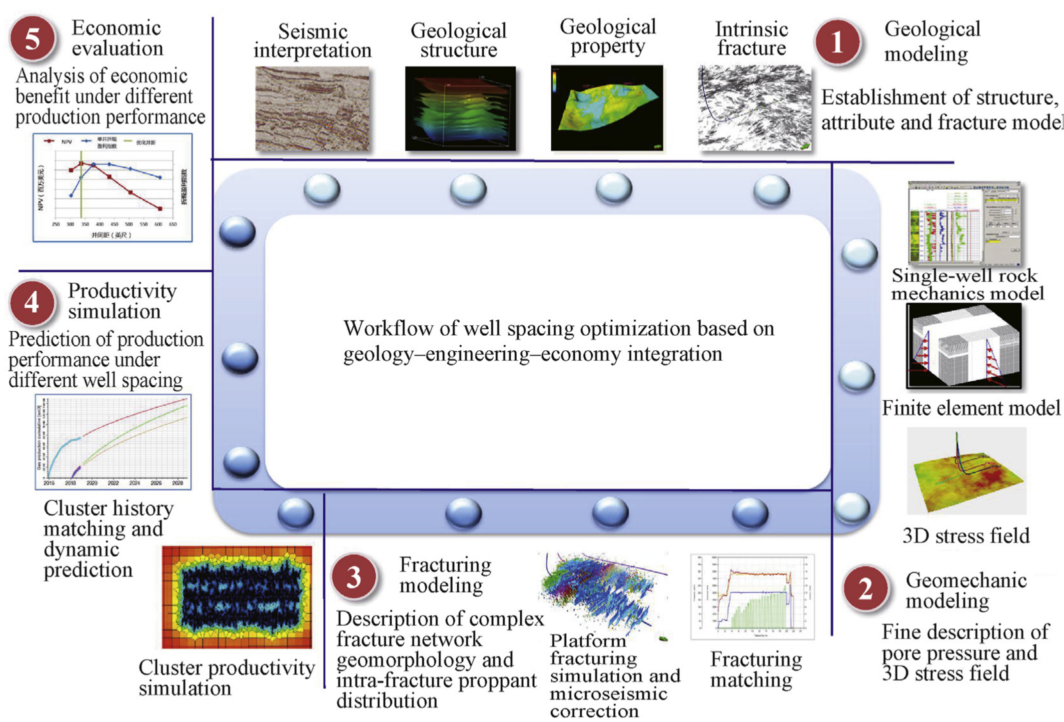

Fig. 11. Workflow of well spacing optimization based on geology−engineering−economy integration.

The changes in the *EUR*, recovery factor and IRR with well spacing are plotted on one graph (Fig. 10). When the well spacing is greater than 240 m, the IRR can be 8%, and the entire platform production is economic; however, the *EUR* can be further improved. When the well spacing is increased to 380 m, the IRR is 16.9%, which indicates that the economic benefit approaches the maximum, but the platform recovery factor has dropped to 42%. To balance the single well *EUR*, platform recovery factor and economic benefits, it is reasonable to control the well spacing between 330 and 380 m. Hence, the minimum well spacing cannot be less than the intersection of *EUR* and recovery factor, and the maximum

5. Conclusion

Well spacing is very significant for the design of shale gas development. However, no two shale gas reservoirs in the world are exactly the same. The differences in geological characteristics, engineering technology, and even gas price will change the reasonable well spacing. It is necessary to use the idea of geology−engineering−economy integration to comprehensively study the reasonable well spacing.

(1) When the well spacing is reduced from 500−600 m to 300−400 m, the probability of well interference in the Changning block gradually increases. Well interference

dominantly takes place in a certain section or several sections, but not across the wellbore. Gas field pressure monitoring and production data changes cannot be used to judge whether the well spacing is reasonable.

(2) Based on the workflow of geology−engineering integration in North America and combined with the domestic economic evaluation method, the demonstration of shale gas well spacing can simulate the production effect of gas wells after induced fractures are connected, and also consider whether the net profit of the scheme and the design of platform number of wells are reasonable.

(3) In Well Block Ning 209, under the current geological understanding and engineering technical conditions, the reasonable well spacing range that takes into account the single well *EUR*, the platform recovery and the economic benefits of development is 330−380 m.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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