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Production Estimation Model of Unconventional Gas Field under Technological Progress – From the Perspective of the Whole Gas Field

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Abstract: Recently, the success of exploitation of unconventional gas has significantly changed the global energy supply. Different from the conventional gas, it is difficult to estimate the single-well production of an unconventional gas field due to the rapid decline of production curve and new wells installed consecutively. The unconventional gas industry is a highly technology-intensive industry and depends on the rapid technological progress. In this paper, we propose to investigate the influence of technological progress on the exploitation of unconventional gas from the perspective of the development cycle of a gas field and establish the production estimation model of unconventional gas under technological progress. The model finds that technological progress could increase total production and extend exploitation cycle by increasing the production rate and recovery ratio of an unconventional gas field. Based on the field's proven reserves and decline discipline of the single-well production, the model could calculate annual production and drilling scheme quickly. Therefore, the model is not only beneficial to the quick decision of investors' economic valuation but also the sustainable exploitation of the unconventional gas field.

Keywords: *unconventional gas; technological progress; field's production; drilling demand; economic efficiency; sustainable exploitation*

1. Introduction

Due to the worldwide rapid growth of the consumption demand for natural gas, the consumption on natural gas is also increasing dramatically. In China, urbanization and industrialization develop rapidly, economic growth is accompanied with rising demand for energy, and the increasing rate of the energy consumption speeds up along with the acceleration of urbanization and industrialization transformation [1]. Moreover, with the increasing attention on the environmental conservation, the Chinese government decides to optimize the energy consumption structure by increasing the proportion of natural gas consumption. It is increasingly claimed that the world is entering a 'golden age of gas', with the exploitation of unconventional resources expected to transform gas markets around the world [2]. However, the conventional natural gas is not enough to meet the demand all over the world in the future and China has become a net importer of natural gas at present [3]. Therefore, to improve the energy consumption structure, China also gradually focuses on the development and utilization of the unconventional energy, especially unconventional gas.

In China, generally, unconventional gas includes shale gas, coalbed methane, tight gas, natural gas hydrate, etc. However, there is transitivity between conventional and unconventional natural gas and the boundary line may change along with the technical level and gas price. Sometimes this section of the natural gas can be classified into the economically inefficient resources in China. In China, the proven reserves of unconventional natural gas is several times that of conventional natural gas. Recently, because of the technological breakthrough, the conventional production gets great increasing and the marketization of unconventional gas develops gradually in some countries, such as the United States. China also accelerates the development of conventional gas in Ordos, Daniudi and northern Yulin basins, striving to meet more than seventy percentage of the domestic gas demand by 2020 [4]. To judge whether domestic gas supply will achieve the goal, the field production is the most important indicator which reflects a field's supply ability. In the previous study, scholars developed many production estimation models to predict single-well and predict a field's production curve based on single-well production.

Scholars conduct many studies on the estimation of single-well production curve of unconventional natural gas [5-8]. At present, based on the principle of different decline curves, many scholars carry on the work estimating single-well production [9-12]. Mao et al. performs a simulation of the production of the plugged and abandoned wells [13], and then predicts the economic reserves of the horizontal well in Sulige gas field based on the static method [14]. Moreover, many studies indicate the significant effects of geological features on single-well production. [15]. Furthermore, with the data of single-well production, many scholars attempt to predict production by other mathematical approaches [16, 17].

At the respective of a field's production estimation, existing studies mainly estimate a field's production curve by accumulating the annual total single-well productions. According to the practical experience and theoretical analysis, a field's production curve tends to increase first and then decline rapidly after a period of stable production. By accumulating the single-well productions during the whole lifecycle, the production distributions of the gas fields have the similar features [18]. Moreover, the theoretical model can also present the production characteristics and estimate the global gas production in the direction from gas fields, basins, to countries [19]. Based on the reserves data of unconventional gas, a self-learning expert system (SeTES) is developed to analyze, design, and forecast the production [20]. In addition, some other scholars also predict the lifecycle and estimated reserve of a field by the production forecast model in the decline production stage [21].

So far, scholars still carry on the development of new predicted approaches with less constrained conditions. However, the single-well production of unconventional gas decreases rapidly. In order to ensure the stable and high yield, many technologies are widely adopted, such as the infill drilling and fracturing technologies. Furthermore, due to the effects of different technical solutions and geological features, the single-well production fluctuates dramatically even in a same gas field. Thus, it is challenging to estimate the single-well production correctly. In addition, it will take a long time to develop a gas field. Although a field's production curve can be estimated by cumulating single-well productions during the full lifecycle by petroleum engineering methods, it cannot meet the urgent requirement in the investment decision, strategic planning and market analysis before large-scaled development. Only with quick and scientific decision could a gas field be developed sustainably with economic benefits. Therefore, to meet the quick investment decision and strategic plan, it is significant to establish the field's production estimation model from the perspective of the gas field.

The production of unconventional natural gas is influenced by technological progress dramatically. Without advanced technologies, for the same or similar gas fields, the difficulties in the exploitation and development of unconventional gas in China are larger than those in the United States. The difficulties cause the low economic efficiency of China's unconventional gas projects and hamper the commercial and sustainable development of China's unconventional gas. It can be seen that it is necessary to take the technological progress' effects into consideration in the production estimation. Therefore, the paper aims to establish the production estimation model of unconventional gas field under technological progress.

The contribution of the paper mainly focuses on the establishment of production estimation model of unconventional natural gas under technological progress from the perspective of the whole gas field. Different from previous model, with the certain reserves and drilling scheme, this model could estimate the production curve of the whole field without the consideration of geological features and the effects of technological progress on the production curve. The model could help producers and investors make strategic decision quickly and efficiently.

The remaining content of the paper is organized as follows. Section 2 is a brief introduction of the effects of technological progress on the field's production of unconventional natural gas. Section 3 is the explanation of the production estimation model. Section 4 shows results of model test and scenario analysis. Section 5 is the main conclusion and the prospect of future research.

2. Technological progress' effects on the production of unconventional natural gas

During the exploitation and development of unconventional gas, technological progress has great effects on field's production in many ways.

Firstly, a series of new technologies could improve the recognition ability and the economic efficiency of unconventional reservoir [22-25]. With the constantly understanding of geological features and technological progress in the exploitation, the field's production in Sulige and Daniudi is promoted to 106 and 22.8 million cubic meters in 2010 respectively and is predicted to reach 230 and 35 million cubic meters in 2020, respectively [26].

Furthermore, the practical experience in the United States shows that infilling drilling has the advantage of expanding reserves, improving the producing degree of reservoirs and increasing production [27-29]. Horizontal drilling technologies are also deployed to attempt success in the Manville and in Nova Scotia [30].

In addition, the fracturing stimulation technology is the key to the success of the unconventional gas development. According to the different characteristics of shale gas reservoir, the United States adopts a series of fracturing technologies and the production of shale gas increases year by year [31-33].

By summarizing the effects of technological progress on gas field's production, the benefits of the technological progress are two-fold. On one hand, technological progress can accelerate the field's production speed. On the other hand, technological progress can increase the recovery rate of a gas field. Based on the two advantages of technological progress, the paper establishes the field's production estimation model of unconventional gas under technological progress in the next section.

The unconventional gas production based on a field is generally divided into three stages: production capacity construction, production plateau and production decline. With the goal to get more ultimately recoverable reserves, the exploitation schedule always remains steady. Thus, the paper assume that the production capacity construction and production plateau remain as the same as that in original schedule. Based the hypothesis, the following is the detailed derivation of the field's production estimation model under technological progress.

3.1. General production estimation model

In the United States, the exploitation of the unconventional gas has a long history. Take the coalbed methane (CBM) as an example, the CBM production in New Mexico and Colorado go through the three stages mentioned above (refer to Figure 1a). At present, Sulige gas field is the biggest unconventional gas field in China. As drilling schedule, Sulige will construct the production capacity of 25.3 billion cubic per year from 2006 to 2014 and maintain the production for 20 years. After then, Sulige will step into the production decline period until the production capacity reduces to a specific degree. The production distribution during the production is shown in Figure 1b. It is obvious that there are some significant similarities in the production characteristics between China and the United States despite many differences in geographical features and development technologies.

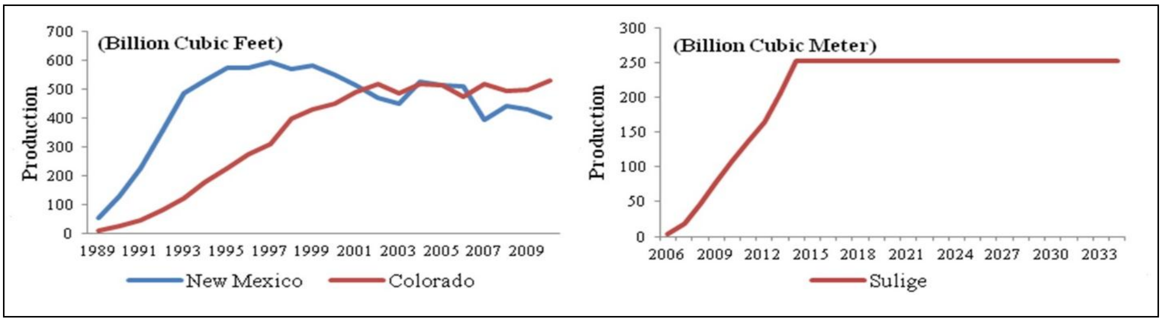

Figure 1.*Comparison between the field's production curve in China and the United States.*
[*The production data in New Mexico and Colorado is from the website of U.S. Energy Information Administration. https://www.eia.gov/ The production data in Sulige is from Economics and Technology Research Institute (ETRI), China National Petroleum Corporation (CNPC). In Sugilge, actual data is from 2006 to 2012 and planned value is from 2012 onwards.*]

Thus, regardless of the heterogeneities in geological features and technologies, the general field's production curve is shown as Figure 2. As Figure 2 shows, the development cycle of unconventional natural gas can be divided into three stages. In Figure 2, M is the production capacity target, a (0<a<1) is the critical condition of halting production and usually equal to 10%, and T_i (i = 1, 2, 3) represents the terminated year of each development stage, respectively.

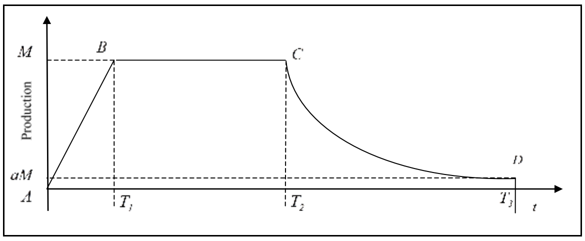

Figure 2.*Field production distribution under a certain drilling schedule*

The first development stage is the production capacity construction stage for which production curve trends to be roughly straight upward until reaching the production capacity target (M). The second development stage is production plateau stage and the producers make produce scheme based on the production capacity target for years (generally 20 years in China). The last stag, production decline stage, will not drill new wells anymore and continue producing until the annual production drop to aM. With the assumption that the field's production decline curve is exponential function, it's easy to obtain the production function (refer to Formula 1) from the production curve showed in Figure 2.

$$Q(t)=\begin{cases} 0 & t<0 \\ \dfrac{Mt}{T_1} & 0\le t\le T_1 \\ M & T_1<t\le T_2 \\ M\cdot e^{b(t-T_2)} & T_2<t\le T_3 \\ 0 & t>T_3 \end{cases} \qquad (1)$$

In Formula 1, $Q(t)$ is field's annual production; t is the year; b is a constant depending on the remaining recoverable reserve in the decline stage, Q_3. Then, the relationship of proven reserves (GR) and ultimate recoverable reserves (EUR) of a gas field can be expressed by Formula 2.

$$GR \cdot r = EUR \tag{2}$$

Where, r is the ultimate recovery ratio.

Generally, the producer stops drilling new wells to stabilize production when the current accumulated production reaches the s percentage of the ultimate recoverable reserves. Then, we can obtain the Formula 3:

$$\begin{aligned} Q_1 + Q_2 &= 0.5 \cdot MT_1 + M \cdot (T_1 - T_2) \\ &= s \cdot EUR = s \cdot r \cdot GR \end{aligned} \tag{3}$$

Where, Q_1 and Q_2 are the cumulative productions in production capacity construction stage and production plateau stage, respectively. Then, we can obtain T_2 as Formula 4 shows.

$$T_2 = \frac{2s \cdot r \cdot GR + MT_1}{2M} \tag{4}$$

Based on the shut-down threshold that annual production drops to aM $(0 < a < 1)$, derived from Formulas 5.

$$Me^{b(T_3 - T_2)} = aM \tag{5}$$

Then, shut-down year T_3 can be obtained.

$$T_3 = (\ln a)/b + T_2 = T_2 - Q_r \ln a / (M(1-a)) \tag{6}$$

Where, T_3 can also be regarded as the lifecycle of the gas field, $b = M(a-1)/((1-s) \cdot r \cdot GR)$.

3.2. Production estimation model under technological progress

Unconventional gas development relies on a variety of techniques, such as exploration technologies, drilling technologies, completion technologies and stimulation technologies. As showed in Figure 3, by increasing the single-well production and slowing down the field's production decline, these technologies could increase comprehensively the production speed and recovery ratio [27-33]. Ultimately, the technological progress could shorten the production capacity construction stage and extend the production plateau in the lifecycle of a conventional natural gas field.

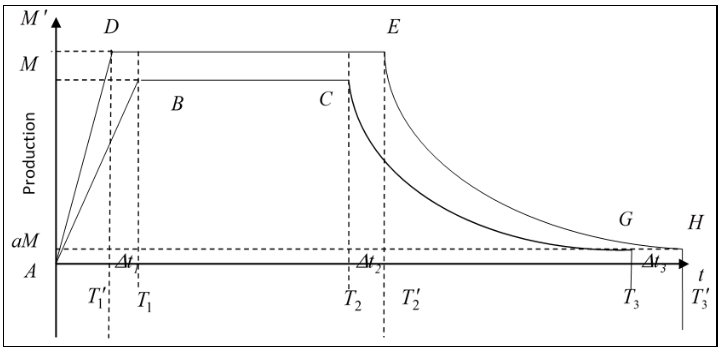

Figure 3.*Field's production curve under technological progress*

EUR can be also regarded as the total production of the field. Therefore, given EUR, T_1, T_2, T_3, and b, it can derive the production distribution of the field.

Based on the general production estimation model, the paper can investigate the effects of technological progresses on the production. However, due to the heterogeneity of unconventional natural gas fields, there are significant differences in the effects of technological progress on the production of unconventional natural gas fields. The heterogeneity brings many difficulties to the definition and measure of the effects of technological progresses on the production curve of conventional natural gas uniformly. Thus, according to the effects of technological progresses on the field's production mentioned in Section 2, the paper integrates these technological progresses into the two factors. The two factors (α and β) reflect the effects of technological progress on the growth rates of production speed and ultimate recovery ratio. After introducing α and β, the production curve formula is shown as Formula 7. By utilizing α and β estimated by production specialists, the model can estimate the field's production curve under technological progress. Generally, based on practical experience, production specialists could predict the effects of the possible improvement or innovation in the technical portfolios on the field's production in a near future.

$$Q(t)' = \begin{cases} 0 & t < 0 \\ (1+\alpha)\dfrac{Mt}{T_1'} & 0 \le t \le T_1' \\ (1+\alpha)M & T_1' < t \le T_2' \\ (1+\alpha)M \cdot exp(b'(t - T_2')) & T_2' < t \le T_3' \\ 0 & t > T_3' \end{cases} \tag{7}$$

Where, $EUR' = r \cdot (1+\beta) \cdot GR$, $T_i' = T_i \pm \Delta T_i$ (i = 1, 2, 3), and $T' = T_3' = (\ln a)/b + T_2'$.

Generally, the development scheme has been determined before the large-scale development of a gas field and it is difficult to adjust the drilling scheme substantially due to the high adjustment cost. Thus, the drilling scheme is almost stable after the scheme is determined. Based on the hypothesis that the original production capacity construction schedule is constant, the production curve is adjusted as shown in Figure 4. By increasing the single-well production, technological progresses can increase the maximum field's annual production and mitigate the field's production decline. The excess production brought by the technological progresses is the area of ABH, HBCG and GCDEF (refer to Figure 4).

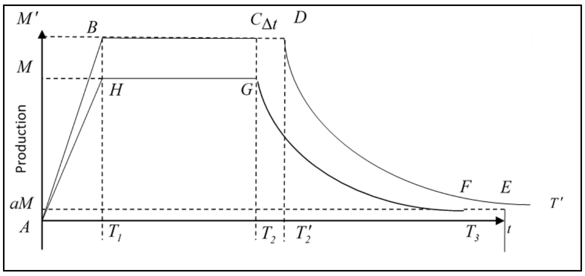

Figure 4.*Production distribution with a given drilling schedule under technological progress*

Then, the terminal year of the production plateau stage and lifecycle (or production decline stage) under technological progresses can be calculated by the Formulas 8 and 9.

$$T_2' = \frac{2s \cdot r(1+\beta) \cdot GR + (1+\alpha)MT_1}{2M(1+\alpha)} \quad (8)$$

$$T_3' = \frac{\ln a}{b'} + T_2{}' \quad (9)$$

Thus, the extension of production plateau stage under technological progresses Δt is as Formula 7.

$$\Delta t = T_2' - T_2 = \frac{s \cdot r \cdot GR \cdot (\beta - \alpha)}{M(1+\alpha)} \quad (10)$$

In Formula 10, it can be seen that the extension of production plateau stage depends on α and β. When production speed increases less than recovery ratio (α<β), technological progresses could extend the production plateau stage; when production rate increases more than recovery ratio (α>β), technological progresses could shorten the production plateau stage; when α=β, the production plateau is invariant.

Under the assumption that the initial annual single-well production (q_1) declines by year with a constant decline rate, we can obtain the distribution of the drilling schedule based on the production estimation model and the principle of the single-well production. The formula is as follows:

$$n_t = \begin{cases} \dfrac{Q_1}{q_1} & t = 1 \\ \dfrac{Q_t - \sum_{i=1}^{\min(m-1,t-1)} q_{i+1} \cdot n_{t-i}}{q_1 \cdot (1-\sigma) \sum_{i=1}^{t-1} n_i} & t \in [2, T] \end{cases} \quad (11)$$

Where, m is the single-well operating stage, n_t is the drilling amount in year t, σ is the decline rate of the initial single-well production, q_t is the single-well production in year t.

4. Results and discussion

4.1. Accuracy test

In the section, in order to test the accuracy of the production estimation model, the paper takes Sulige gas field as an example. Sulige gas field starts into a wide range of exploration in 1999, and the proven reserves is 220,475 billion cubic meters by early 2001. In 2003, the proven reserves increase by 313.177 billion and become the largest gas field in China with an accumulative proven reserves of 533.652 billion cubic meters.

According to the schedule, the producers plan to construct the production capacity of 25.3 billion cubic meters per year from 2006 to 2014. Actually, due to the three-year natural plateau of single-well production, it begins to construct new production capacity in 2009 and the drilling amount increases by years [34]. After the construction completion in 2014, the producers only drill wells to make up the production decline until the end of the production plateau of the field and the drilling amount is nearly stable during the period. The single-well lifecycle is 20 years tentatively. The relevant data of Sulige gas field, which is from ETRI, CNPC, is showed in Table 1.

Table 1*.The production and drilling schedule of Sulige gas field*

Year	Production (100 million cubic feet per year)	Drilling Amount per year		
		Normal wells	Infill wells	Total
2006	2.8	315	0	315
2007	18	809	0	809
2008	46.1	1014	0	1014
2009	78.1	818	80	898
2010	107.5	1277	257	1534
2011	137.5	1027	302	1329
2012	165	657	317	974

The comparisons of production and drilling demand between calculated results and historical data are as shown in Figure 5 and Figure 6, respectively. The paper assumes that per-well production curve in Sulige gas field follows the discipline of Aprs hyperbolic decline curve [13, 14]. It shows that the difference in the field's production between the simulated values and the historical data reduces gradually over the time, while the difference in the drilling demands is larger. The difference in drilling demands may be caused by the fluctuated single-well production. The fluctuation in single-well production could be greatly influenced by artificial factors so that the practical single-well production does not fully comply with the principle of Aprs hyperbolic decline curve.

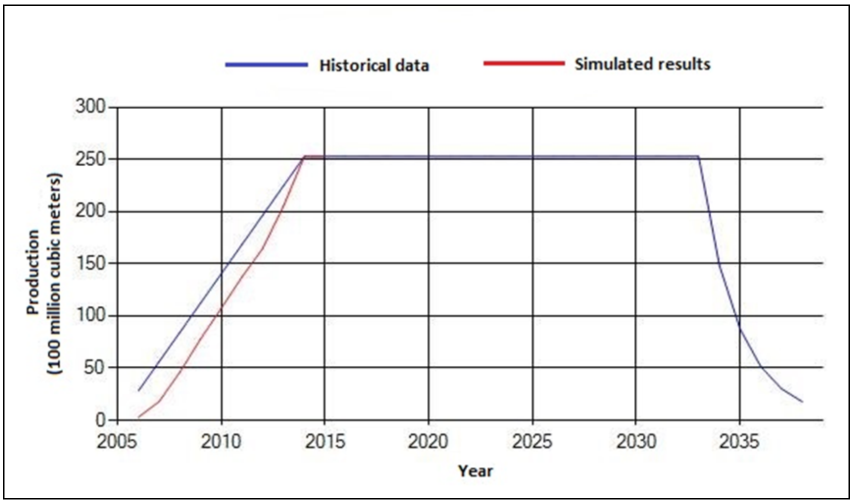

Figure 5.*Comparison in field's annual production curves*

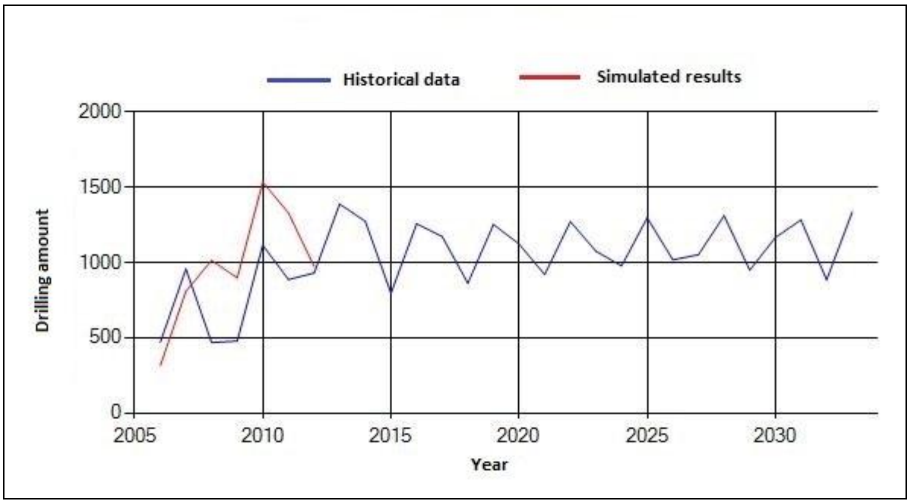

Figure 6.*Comparison in drilling schemes*

Therefore, given the basic information of the reserves, production capacity target, and the principle of the single-well production, the model can estimate the production distribution and drilling demand of the gas field in the lifecycle, and provide investment decision, strategic plan, and market analysis with the quick and scientific supports.

4.2. Scenario analysis

In the section, the paper sets up some referenced technological progress scenarios by assigning different technological progress factors, α and β. For example, the paper assigns zero to α and β in the scenario without technological progress and assigns α and β with 10% in the TP1 scenario, respectively (see Table 2). By comparing the estimated production curve in different technological progress scenarios, we can obtain the technological progress' effects on the field's output efficiency, such as extension of production plateau stage and production lifecycle.

Furthermore, each referenced scenario includes three technical portfolios: referenced portfolio, fast portfolio and slow portfolio. Referenced portfolio is the technological progress which is reckoned to be the most likely to occur and the portfolio's α and β can be estimated by practical specialists. In fast and slow portfolios, the speed of technological progress is 120 percent and the 80 percent of those in the reference portfolio. With these technological progress scenarios, relevant results estimated by the model are shown in Table 2.

Table 2.Output efficiency comparison under different technical scenarios

	Referenced technological progress (TP)		Extension of production plateau		Extension of production lifecycle	
	α (%)	β (%)	Fast (year)	Slow (year)	Fast (year)	Slow (year)
With no TP	0	0	0	0	0	0
TP1	10	10	0	0	0	0
TP2	10	30	4	3	3	2
TP3	30	10	-5	-4	-4	-3

When the growth rate of production speed (α) equals the growth rate of recovery ratio (β), the length of production plateau and production lifecycle remain unchanged though technological progress increases the field's production speed and recovery ratio simultaneously (see TP1 in Table 2). Meanwhile, the results of TP2 in Table 2 show that the technological progress extends the length of production plateau and production lifecycle when the growth rate of production speed (α) is higher than the growth rate of recovery ratio (β). However, when α is bigger than β, technological progress will shorten the length of production plateau and production lifecycle because of the too fast production speed brought by technological progress.

Therefore, it follows that different technological progress portfolios all could increase the field's production speed and recovery ratio, however, the length of production plateau and production lifecycle are affected comprehensively by the two technological progress factors.

In practice, hydraulic fracturing, infill drilling and horizontal drilling are widely used in the development of unconventional natural gas. These drilling and stimulation technologies could increase producers' economic efficiency by increasing field's production dramatically. However, it is also necessary to maintain the sustainable development of unconventional natural gas. The stratum structures of gas reservoirs could be damaged by the overquick development. In other words, not only economic efficiency but also reservoirs' sustainability should be considered into producers' production scheduling.

5. Conclusion

By analyzing various aspects of technologies in the exploitation and development of unconventional natural gas field, the paper integrates various aspects of technology progress into a technological progress factors (α and β) which reflect the effects of technological progress on production speed and recovery ratio. And then investigates the influence of the technological progress on the field's production in an unconventional gas in China by introducing technological progress into the model. For the unified development cycle of the entire field, the paper develops production estimation model of unconventional gas under technological progress. The model could estimate field's annual production and drilling scheme quickly.

Different from previous production estimation models, the paper contributes a theoretical model to estimate field's annual production from the perspective of a gas field. Previous production estimation models are set up from bottom to up, while the paper's model is constructed the macro level of the entire gas field. The theoretical model provides scientific basis for the investment decision, strategic plan and market analysis quickly and lays the foundation for the further study on the issue in the future.

However, the model still needs to be improved to meet the practical need. Due to lack of the data of the effects of development technologies on production, it is impossible to estimate the production changes under different technological portfolios at present. In the future, the study will focus on the quantitative relation between the annual field production and a single-well production in order to improve the accuracy of the drilling demand model. In addition, the correlations with technological progress factors and the actual technological portfolios are also an important work to improve the actualization and objectification of the measurement of the technological progress.

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