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Review

Forecast of oil reserves and production in Daqing oilfield of China

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ABSTRACT

As China' largest oilfield, Daqing is of great importance to China, this paper analyzes the status of the Daqing oilfield and forecasts its ultimate recoverable reserves by use of the *URR* model. The forecast results are presented for three scenarios which show that the ultimate recoverable reserves in Daqing oilfield are 3574.0 million tons in the optimistic scenario, 3169.3 million in the base case scenario and 3033.3 million in the pessimistic scenario, respectively. A system dynamics model is established and the quantitative relationships between variables in the model are determined. Total oil production, remaining recoverable reserves, annual newly discovered reserves, and the degree of reserves recovery before 2060 are simulated under the three scenarios by use of the system dynamics model. The forecast results show that the future oil production in Daqing oilfield will continue declining, under the base case scenario, from 41.6 million tons in 2007 to 8.0 million tons in 2060. For Chinese policy-makers, it is worth paying attention to the problem of whether oil production in new oilfields can effectively make up for the decline in production of the large, old oilfields.

1. Introduction

Robelius [1] found that giant oil fields are very important to the world oil production and for many countries' domestic oil production. The Cantarell field in Mexico accounted for over 50% of the total Mexican production in 2005. Campbell [2], Hirsch [3], Meng, and Bentley [4] also have pointed out the importance of giant oil fields.

Daqing oilfield is among of the largest oilfields in the world and is China's largest. Fig. 1 shows the location of Daqing within China. The field had already produced a total of 1.95 million tons of oil by 2007. It has maintained a high and stable yield of more than 50 million tons continuously per annum over the 27 years since oil production exceeded 50 million tons in 1976. After decades of high speed and high efficiency development, production in the Daqing oilfield has been decreasing since 1997. The annual production declined from the peak production of 56.0 million tons in 1997 to 41.6 million tons in 2007 – an average decline rate of 2.9% per year. Even though the Daqing oilfield is experiencing decreased production, it still accounts for nearly 25% of China's oil production.

The objective of this paper is to forecast the ultimate recoverable resources (*URR*) and future oil production in Daqing.

2. Analysis of the status of the Daqing oilfield

Fig. 2 shows the annual oil production of the Daqing oilfield and all of China. As can be seen, the Daqing oilfield has obviously made a tremendous contribution to China's oil industry, accounting for an average of 75% of China's yearly oil production throughout the 1960s and 1970s.

After that period, the contribution of Daqing to all of China's oil production gradually declined from a peak of 78.7% in 1964 to 22.4% in 2007. To maintain its important position and realize sustainable development, CNPC (China National Petroleum Corporation) put forward an objective of "establishing a centurial oilfield" (or, in other words, an oilfield that will last a century) in 2004 as pointed out by Yupu Wang [5–7]. The aim of this proclamation was to make the field an important oil and gas production base for China through to 2060, by which year the field will have been exploited for 100 years. As pointed out by Jinguo Chen and Yuqiang Chen [8], establishing a long-term plan is essential to ensuring the Daqing oilfield remains a productive asset to mid-century and beyond.

Fig. 3 shows annual newly discovered reserves and oil production in the Daqing oilfield. Newly discovered reserves in the field peaked in 1973, 24 years before peak oil production in 1997.

Based on a comparison between annual newly discovered reserves and oil production, the development of the Daqing oilfield can be divided into three phases. In the first phase (1961–1975), both annual newly discovered reserves and oil production kept increasing continuously. Furthermore, annual newly discovered

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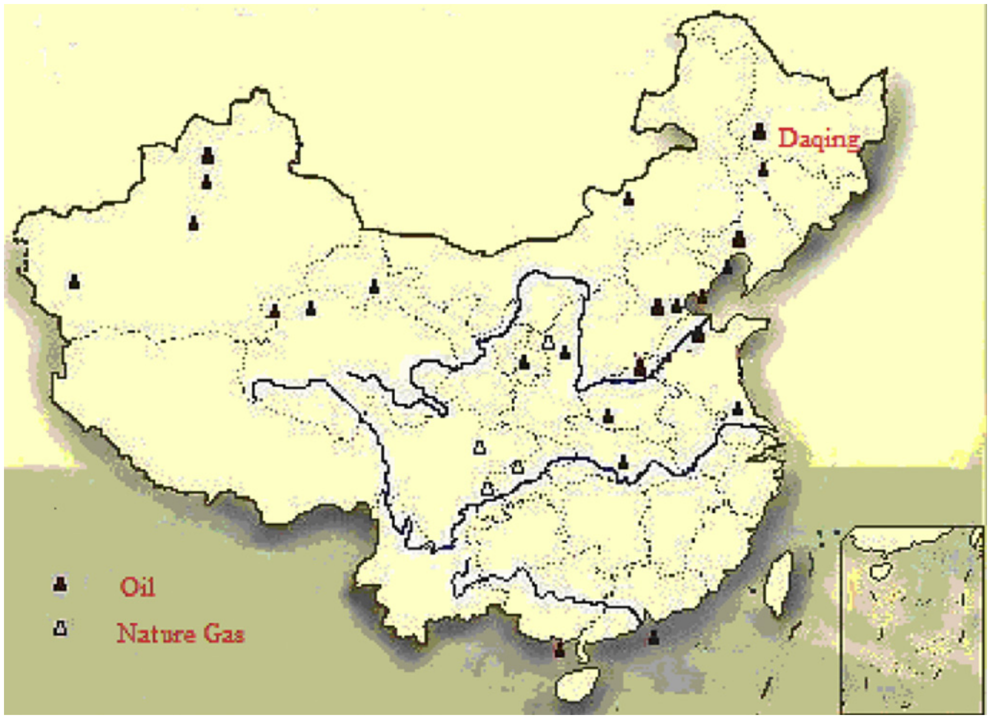

Fig. 1. Location of Daqing oilfield in North East China.

reserves increased faster than oil production, which meant it exceeded oil production every year and the remaining recoverable reserves increased very rapidly.

In the second phase (1976–1991), annual newly discovered reserves were lower than oil produced per year over the period of 1976–1983. Newly discovered reserves then exceeded oil production per year in the period from 1984 to 1991. However, cumulative newly discovered reserves were almost equal to cumulative oil production over the whole phase. Thus, remaining recoverable reserves remained stable.

In the third phase (1992-present), annual newly discovered reserves declined and were less than oil production in each year. Remaining recoverable reserves consequently declined rapidly.

3. Forecast of oil reserves in the Daqing oilfield

3.1. Introduction of the URR model

There are many different ways to model the reserves of an oil field. Decline curves, probabilistic methods, stochastic approaches, and much more have been utilized for reserve estimations. These are described in various studies, such as Li & Horne [9], Chang & Lin [10] and Ayeni & Pilat [11]. This article utilizes a different reserve estimation model. The following equations and formulas provide the basis for the *URR* estimation technique used here.

Wenbo Weng [12], Xudong Zhao [13], Fusheng Huang et al. [14] showed that the degree of *URR* recovery (R_D) in an oilfield will change as more historic data becomes available and the development time (t) increases. The relationship between R_D and t is reflected in the following formula (1).

$$\lg\frac{R_D}{1-R_D} = A + B\lg t \tag{1}$$

both A and B are constants which can be determined by linear regression.

Formula (1) has been successfully testified by Chinese oilfield data, and it is mainly used to estimate R_D in the future to know the development phase of the oilfield. In fact, it can be further used to estimate the *URR* as follows:

Formula (1) can also be described as Formula (2),

$$R_D = \frac{1}{1+10^{-A}t^{-B}} \tag{2}$$

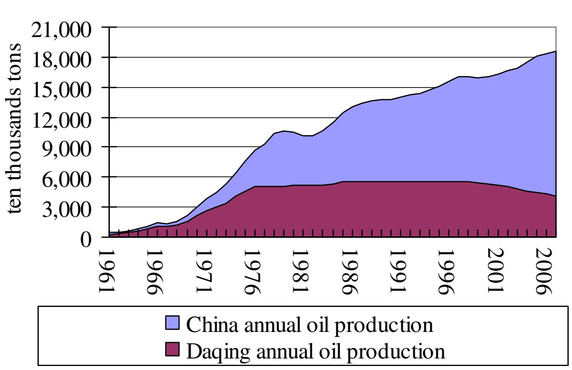

Fig. 2. Annual oil production in Daqing and China.

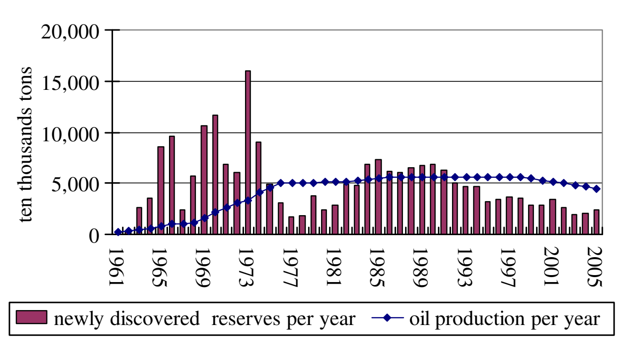

Fig. 3. Annual newly discovered reserves and the oil production in Daqing oilfield.

R_D can be substituted by N_p/URR, where, N_P is accumulative oil production.

Then Formula (2) can be described as Formula (3),

$$N_P = \frac{URR}{1 + 10^{-A}t^{-B}} \tag{3}$$

Q (oil production per year) which is the derivative of N_P can be obtained from formula (3),

$$Q = \frac{B \times 10^{-A} \times URR \times t^{-(B+1)}}{\left(1 + 10^{-A}t^{-B}\right)^2} \tag{4}$$

Formula (5) can be obtained from formula (3) and (4),

$$\lg\frac{Q}{N_p^2} = \lg\frac{B10^{-A}}{URR} - (B+1)\lg t \tag{5}$$

Equations (6) and (7) are assumed as follows.

$$\alpha = \lg\frac{B10^{-A}}{U_{RR}} \tag{6}$$

$$\beta = -(B+1) \tag{7}$$

Then formula (5) can be described as equation (8).

$$\lg\frac{Q}{N_p^2} = \alpha + \beta \lg t \tag{8}$$

then α and β can be obtained through linear regression. After getting α and β, the *URR* model can be obtained from equation (3), (6) and (7) as follows:

$$URR = \left[\frac{1}{N_p} + \frac{1}{\beta+1}10^{\alpha}t^{\beta+1}\right]^{-1} \tag{9}$$

Where, *URR* is Ultimate Recoverable Resources; N_P is accumulative oil production which is calculated based on the historical data of oil production (Q);α and β are the regression coefficients got from linear regression in equations(6) and (7);t is the development year of the oilfield. There are no special geologic meaning for parameters α and β, they are just statistic parameters.

3.2. Forecast results of URR

Fig. 4 suggests that there is an approximately linear relationship between $\lg(Q/N_p^2)$ and $\lg t$ in the Daqing oilfield as described in formula (8), especially during the period of 1973–2007.

The historical data over the period of 1973–2007 is used in the linear regression. According to the regression result, α is −0.907 and β is −3.609. The ultimate recoverable reserves in Daqing is then forecast by use of the *URR* model above.

Fig. 5 shows the forecast result of the URR for the most recent 25 years. As can be seen, there are different forecast results of *URR* in different years, due to the different $\lg(Q/N_p^2)$ and $\lg t$ in each year. Table 1 shows the forecast results of URR under three different scenarios: 1) an optimistic scenario, 2) a base case scenario, and 3) a pessimistic scenario. The forecast result in the optimistic scenario is the average between 1982 and 1985, over which the *URR* forecast results are obviously higher than others. The base case scenario is the *URR* average, and the pessimistic scenario is the lowest *URR* between 1982 and 2007.

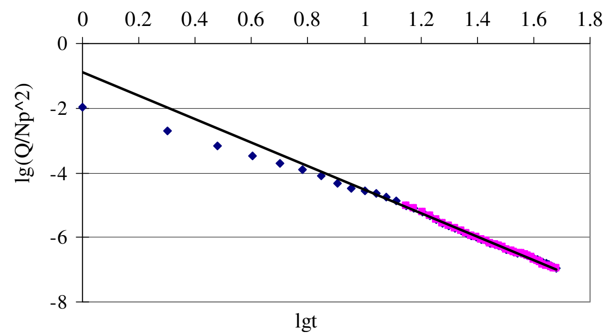

Fig. 4. Linear relationship between $\lg(Q/N_p^2)$ and $\lg t$ in Daqing oilfield.

4. Oil production forecast of the Daqing oilfield

This study uses system dynamics as the methodology to forecast the oil production in the Daqing oilfield. System Dynamics or SD for short, is based on feedback control theory and applied by computer simulation techniques. It is an effective methodology for modeling and analyzing complex social, economic, and ecological systems. It is a subject established on the basis of operations research and synthesizing many subjects such as system theory, control theory, information feedback theory, decision-making theory, mechanical systems, and computer science.

Qipan Wang [15] points out that the most important feature of system dynamics is to elucidate that behavior patterns and characteristics of a system mainly depend on internal dynamic structure and the feedback mechanism. According to the principle that functions of a system are determined by the structure of the system, the system is built as a causal loop diagram. Then, based on the principle of feedback, regulation and control, a feedback loop is designed to reflect behavior of the system. Ultimately, a system dynamics model is established, and furthermore, simulation experiments are made by use of computers, as pointed out by Renan Jia and Ronghua Ding [16].

4.1. System dynamics modeling

According to the basic principle of system dynamics, the oil production forecast model is established as follows:

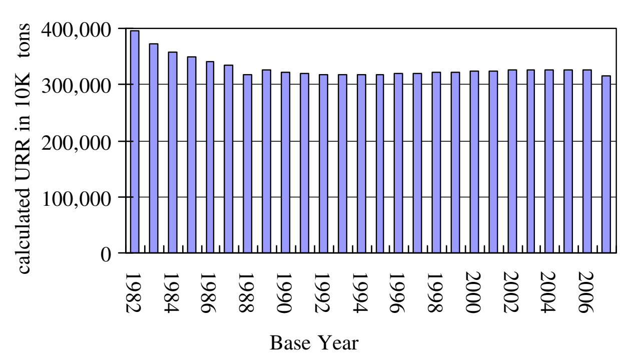

Fig. 5. Forecasted URR in Daqing oilfield varies depending on the historical year chosen in the URR model. Since 1988 it has however been more or less constant.

Table 1
Forecast results of *URR* by 2060 in Daqing oilfield under three scenarios.

Scenarios	Optimistic	Base Case	Pessimistic
URR (tons)	3,573,960,000	3,169,330,000	3,033,270,000

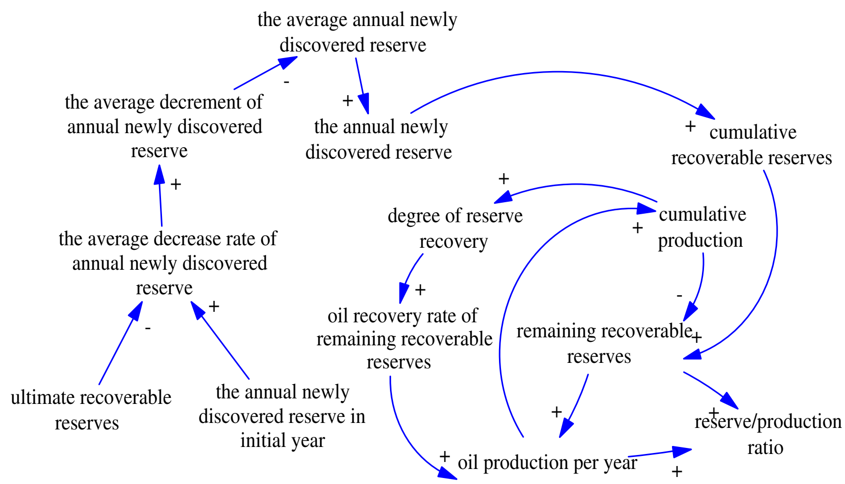

Fig. 6. Causal loop diagram for forecast of the oil production in Daqing oilfield.

4.1.1. Determine the purpose and boundary of the model

The modeling purpose is to establish a concise and efficient model which can reflect the basic oil production process and forecast oil production in the future. In order to make the model more efficient, the boundary, that is the scope of the research object, is determined, and then the necessary and important variables are chosen to compose the model. A total of 13 variables are chosen in this paper, they are annual newly discovered reserves, cumulative recoverable reserves, remaining recoverable reserves, cumulative production, degree of reserves recovery, oil recovery rate of remaining recoverable reserves, oil production per year, reserves/production ratio, the average annual newly discovered reserves, the average decrease of annual newly discovered reserves, the average decrease rate of annual newly discovered reserves, ultimate recoverable reserves, and the annual newly discovered reserves in the initial year.

4.1.2. Establish the causal relationship diagram

A causal relationship diagram reflects the basic relationships between the variables chosen at the last step. Fig. 6 shows the causal loop diagram for oil production modeling in Daqing. As can be seen, the average decrease rate of annual newly discovered reserves is affected by ultimate recoverable reserves and the annual newly discovered reserves in the initial year, and the average decrease of annual newly discovered reserves is determined due to its positive relationship with the average decrease rate of annual newly discovered reserves. Then the average annual newly discovered reserves is determined according to the average decrement of annual newly discovered reserves, and furthermore, the annual newly discovered reserves is assumed to be equal to the average annual newly discovered reserves. Remaining recoverable reserves and the oil recovery rate of remaining recoverable reserves are two key indicators to control oil production per year, and at the same time the oil recovery rate of remaining recoverable reserves is affected by the degree of reserves recovery.

4.1.3. Establish the stock and flow diagram

A stock and flow diagram is based on the causal relationship diagram and prepares for system dynamics simulation. The stock and flow diagram can further reflect the relationships by classifying these variables. As shown in Fig. 7, the average annual new discovered reserves, cumulative recoverable reserves, and cumulative production are chosen for level variables in this model.

4.1.4. Determine model parameters

Determination of model parameters is an important step during system dynamics modeling. Initial values of some variables in the model are determined by the data related to exploration and development of the field. These variables are cumulative recoverable reserves, remaining recoverable reserves, cumulative

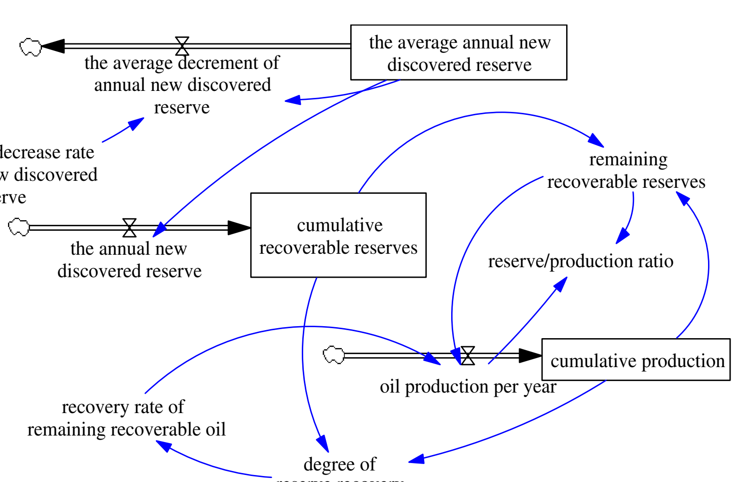

Fig. 7. Stock and flow diagram for forecast of the oil production in Daqing oilfield.

Table 2
Sensitive test results of parameters constancy along time under base case scenario.

Year	Forecast Production	Actual Production	Difference Amount	Difference Rate
2003	4833	4840	−7	−0.15%
2004	4677	4640	37	0.81%
2005	4524	4495	29	0.63%
2006	4372	4338	34	0.78%
2007	4213	4162	51	1.22%
2008	4057	4020	37	0.93%
Average	4446	4416	30	0.70%

production, degree of reserves recovery, and annual newly discovered reserves in the initial year

The value of oil recovery rate of remaining recoverable reserves is determined by historical data fitting. As can be found from the research, there is a positive correlation between oil recovery rate of remaining recoverable reserves and the degree of reserves recovery in Daqing oilfield. The regression equation is $Y = 0.072978X + 0.032879$, in which Y stands for the recovery rate of remaining recoverable oil and X stands for degree of reserves recovery. The regression equation has passed the F-test as well as the *t*-test and the goodness-of-fit reached 95.6%.

The value of the average decrease rate of new recoverable reserves per year is determined by the value of ultimate recoverable reserves and new recoverable reserves in the initial year. Moreover, the average decrease rate of new recoverable reserves per year has three values: 0.9% in the optimistic scenario, 2.0% in the base case scenario and 3.2% in the pessimistic scenario. This is due to the different values of ultimate recoverable reserves in these three scenarios.

4.1.5. Test the constancy of parameters along time

In order to know how sensitive the forecasts are to the forecast origin, the constancy of parameters along time is tested in this paper. Thus, the forecast origin is changed to 2002, and then the forecast results are compared with the actual data from 2003 to 2008. Table 2 shows the sensitivity of test results of parameters constancy along time under the base case scenario. It can be easily found that the parameters constancy is good. The average production difference between forecast production and actual production is 30 tons, and the difference rate is just 0.70%.

4.2. Forecast results

Based on the system dynamics model established above, the main parameters and the quantitative relationship between

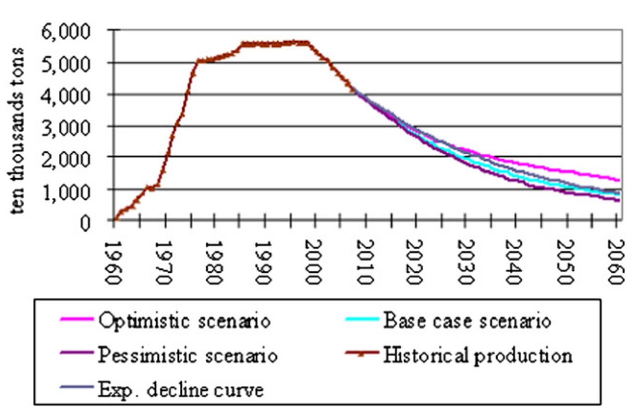

Fig. 8. Model results of the oil production in Daqing oilfield along with an exponential decline curve fit.

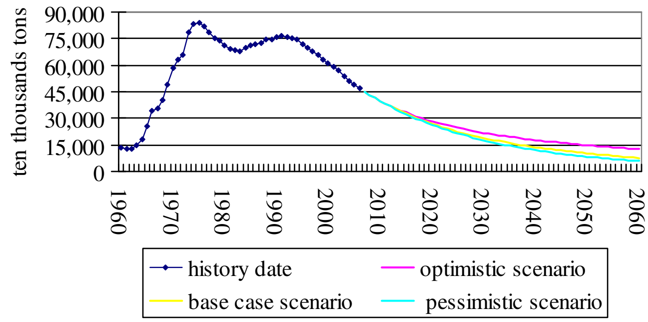

Fig. 9. Model results of the remaining recoverable reserves in Daqing oilfield.

variables in the model are determined in this paper. The following are simulation results of the oil production, the remaining recoverable reserves, the annual newly discovered reserves, and the degree of reserves recovery before 2060 under three scenarios by use of the SD model.

In Fig. 8 a future production outlook from the SD model can be seen. An exponential decline fit, based on the decline curves proposed by Arps [17] and Fetkovich [18], has also been included to serve as a simple comparison. More complex methods, such as Chang & Lin [10], can of course be used for a more comprehensive comparison, but this is beyond the scope of this study. From the simple comparison presented here one can see that the SD model forecasts ends up around the same production levels that a more traditional methodology would have yielded.

However, these results should also be compared with other studies of giant oil fields. Gowdy and Julia [19] examine two giant oil fields from the North Sea and West Texas and draw the conclusion that new technology masks increasing oil scarcity rather than greatly improves the amounts of recoverable volumes. More studies of how technology has influenced the recoverable volumes of Daqing should be conducted to better understand the issue.

Babadagli [20] concludes that development of mature fields is becoming increasingly more attractive, but remains challenging. Long term planning and clear identification of the goals is needed for a successful undertaking, but this is mainly made difficult by uncertainty in oil price and other instabilities. Implementing lessons and experience from other giant oil fields and development of mature regions is essential for a smooth transition towards the future.

As shown in Figs. 9 and 10, the remaining recoverable reserves and annual newly discovered reserves in the Daqing oilfield decline continually. In Fig. 11, the degree of reserves recovery in the Daqing oilfield increases continually in each scenario, from 0.8 in 2007 to nearly 1 in 2060. This behavior is well in line with the increasing maturity of the Daqing oilfield.

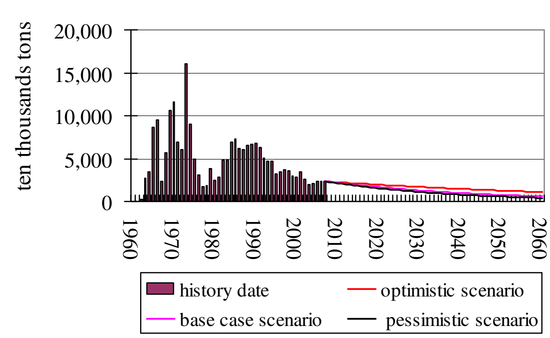

Fig. 10. Model results of the annual newly discovered reserves in Daqing oilfield.

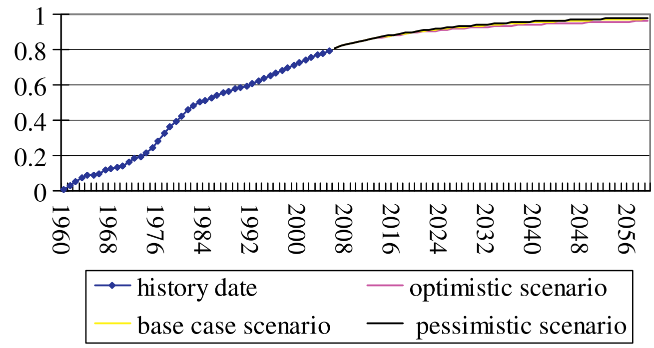

Fig. 11. Model results of the degree of reserves recovery in Daqing oilfield.

5. Conclusions

Scenario analysis of ultimate recoverable reserves and long-time simulation of oil production in the Daqing oilfield, based on the *URR* model and the system dynamics model respectively, can provide a strategic decision basis for establishing a centurial oilfield for Daqing by showing some possible future outcomes. Conclusions are as follows:

(1) It is of great importance to forecast the ultimate recoverable reserves, due to their obvious impact on oil production. In this paper, the ultimate recoverable reserves have been forecast and analyzed under three scenarios. Exploration of old fields in Daqing is relatively mature. Future exploration will focus on the external areas around Daqing such as the Halar basin in Inner Mongolia, as pointed out by Meng, X. et al. [21]. Differences between the three scenarios will mainly depend on the achievements of exploration in the external Daqing region. Complementing other *URR* forecasting methods, such as distribution studies conducted by Laherrere, J. [22] or creaming curves by Doust, H. & Noble, R. [23], should also be undertaken to provide a more comprehensive picture of the situation and its possible future outcomes.

(2) Although large investment has been made in exploration of the Daqing oilfield in recent years, it still can not prevent the downward trend of annual newly discovered recoverable reserves. Findings in this paper indicate that the trend will continue, which means the exploration investment is gradually increasing per unit of newly discovered recoverable reserves.

(3) In order to achieve the objective of establishing a centurial oilfield, CNPC (China National Petroleum Corporation) must put forward the strategic planning of supplementing oil with gas. As there is much more uncertainty in the trend of natural gas production than in the trend of crude oil production, the development plan for natural gas in the Daqing oil field should be determined by the general goal of future production of oil and gas and the forecast production of oil.

(4) The future production of oil in the Daqing oilfield will continue to decline. Under the base case scenario, the oil production will decline from 41.6 million tons in 2007 to 8.0 million tons in 2060. Therefore, it is worth thinking about the Daqing oilfield to bring forward a policy of maintaining the annual production of 40 million tons for the next decade. That will be difficult and challenging because petroleum resources are limited and ultimate recoverable resources in the Daqing oilfield will likely never exceed the forecast optimistic value.

(5) The Daqing oilfield is a cornerstone of China' oil industry, not only because of its exceptional past production, but also because it remains important for China's oil security. Oil production in the Daqing oilfield continues to decline, while oil demand in China is growing rapidly and dependence on importing oil is gradually increasing. For Chinese policymakers, it is worth paying attention to the problem of whether oil production in new oilfields can effectively make up for the decline in oil production of the large old oilfields. In long-term, the issue how to deal with energy demand growth, develop renewable energy, balance energy and environment will be more and more important for policymakers as pointed out by Fredrich Kahrl and David Roland-Holst [24], Xiliang Zhang et al. [25], Yiping Fang and Yong Zeng [26].

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