Novel Method of Production Decline Analysis

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Abstract. ARPS decline curves is the most commonly used in oil and gas field due to its minimal data requirements and ease application. And prediction of production decline which is based on ARPS analysis rely on known decline type. However, when coefficient index are very approximate under different decline type, it is difficult to directly recognize decline trend of matched curves. Due to difficulties above, based on simulation results of multi-factor response experiments, a new dynamic decline prediction model is introduced with using multiple linear regression of influence factors. First of all, according to study of effect factors of production decline, interaction experimental schemes are designed. Based on simulated results, annual decline rate is predicted by decline model. Moreover, the new method is applied in A gas filed of Ordos Basin as example to illustrate reliability. The result commit that the new model can directly predict decline tendency without needing recognize decline style. From arithmetic aspect, it also take advantage of high veracity. Finally, the new method improves the evaluation method of gas well production decline in low permeability gas reservoir, which also provides technical support for further understanding of tight gas field development laws.

1. Introduction

Production decline analysis as a fundamental method for production prediction, is closed related to optimization working schedule and formulation of production measures. Bases on ARPS decline curves(exponent, hyperbolic and harmonic) proposed in \textsuperscript{1945}[1], production analysis method is continuously developing ranging from typecurve matching to rate-pressure normalization techniques and detailed production history matching\textsuperscript{[2][3][4][5]}. However ARPS decline curves(despite it's many limitation like constant bottom hole pressure) is still commonly used in domestic and overseas gas field due to its minimal data requirements and ease application\textsuperscript{[6][7]}.

ARPS decline curves refers to using production data of decline stage, via determining decline index(Q\textsubscript{i}, D\textsubscript{i}, n) by correlation coefficient, then to establish empirical formulas realizing future production trend prediction\textsuperscript{[8]}. The key point for this method is decline type determination. Yet low permeability-tight gas reservoir cases studies and experiences demonstrates that coefficient index are very approximate under different decline type(value of correlation coefficients are very closed in the Table 1). In another words, it is difficult to directly recognize decline trend of matched curves or to finish prediction.
Table 1. Contrast results of correlation coefficient for Well X1 in Changqing gas field

| Decline type         | n   | \( Q_0 \) | \( D_i \) | r   |
|----------------------|-----|-----------|-----------|-----|
| Harmonic decline     | 1   | 3.21      | 0.0414    | 0.855 |
| Depletion decline    | 0.5 | 2.49      | 0.0194    | 0.861 |
| Hyperbolic decline   | 0.5 | 2.49      | 0.0194    | 0.862 |
| Exponent decline     | 0   | 2.27      | 0.0123    | 0.851 |
| Linear decline       | -1  | 2.17      | 0.0067    | 0.780 |

As typical low permeability gas field, Changqing face the same problem. Besides, considering features of unstable working schedules (different production rate arrangement with viable bottom hole pressure) and large number of wells, accurate and quick evaluation for production decline is very difficult\[9\]. Therefore, it is necessary to study a method with merits of convenient access to data, ease application and without recognizing decline type.

2. Response surface analysis

Response surface analysis is a research method combining mathematical methods, experimental design and statistical analysis\[10\][11\]. Specifically speaking, it mainly rely on the experiments to obtain a large number of measurement data, then according to responses of the system (or a object) as one or more factors function to establish mathematical model, and finally realize visual analysis. Comparing with traditional single factor analysis, response surface analysis can be quantitative evaluation about multi-factors and their interactions.

Usually, multiple linear regression is effective way to set up the modeling. After modeling, engineers verdict reliability by the difference of calculation and experimental values whether meet the requirements. The qualified one with features such as correlation coefficient (calculated by experimental values and model calculation) is close to 1 or all of the relevant points nearly a straight line.

According to the response surface analysis method principle, decline rate can be set to be output response, while mainly factors which affect rate decline of low permeability gas reservoir are used to design experiments, finally decline rate and rate are predicted without recognize decline type realizing accurately and quickly evaluation.

3. Method

3.1 Production decline approach

From introduction above, research approach is clearly explicated. First of all, the paper designs the experiments of gas well production decline. The former large work demonstrate that multi-factors affect rate which can be summarized as physical parameters, dynamic reserves, field pressure and working schedule (production rate per day arrangement) four aspects. As a result, on the basis of production of gas field, permeability, dynamic reserves, working schedule and field pressure labeled as 4 factors 5 levels and more than 30 design parameters of the experimental group are considered(Table 2). Then setting decline rate as output response (target function) to convey each factors inter-action. Finally numerical simulation method are used to simulate 20 years of production of various projects (simulation results in Table 3).

Table 2. Experiment design parameters

| Permeability (mD) | Dynamic reserves \( \times 10^8 \) m$^3$ | Production rate \( \times 10^4 $m^3$/d$) | Filed pressure (MPa) |
|-------------------|----------------------------------------|----------------------------------------|---------------------|
| 0.1               | 0.4                                    | 2                                      | 10                  |
| 2.07              | 1.3                                    | 3.5                                    | 15                  |
| 4.05              | 2.2                                    | 5                                      | 20                  |
| 6.02              | 3.1                                    | 6.5                                    | 25                  |
| 8                 | 4                                      | 8                                      | 30                  |
The decline rate value from table 3 is used as response of surface analysis experimental. Then regression model of four viable quadratic equation, the years’ decline rate and key elements effects can be simulated. The usually formation is

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \epsilon$$  \hspace{1cm} (1)

### 3.2 Quantitative analysis of main controlling factors

Variance analysis is an effective method to do significant analysis of coefficient from linear equation regression. One aspect of its purpose is determined main controlling factors and multi-factors interaction degree. The other aspect is used to simplified model by removing no significant effect factors. For example of 1st year decline model, from significant analysis of $F, P$ value($F, P$ as dimensionless number of significance test, $F>0.1, P<0.05$ indicates that factor is significant effected), quantitative evaluation results are shown in table 34.

The $F$ value illuminates influence order is dynamic reserves(557.71)$>$ permeability(505.26)$>$ field arrangement $>$ other terms are not significant which can be removed from the final model.
### Table 4. Results of factor interaction

| Factors | F     | P       |
|---------|-------|---------|
| A       | 505.26| <0.0001 |
| B       | 44.13 | <0.0001 |
| C       | 557.71| <0.0001 |
| D       | 8.25  | 0.0111  |
| AB      | 3.32  | 0.0871  |
| AC      | 14.08 | 0.0017  |
| AD      | 0.16  | 0.6919  |
| BC      | 3.27  | 0.0893  |
| BD      | 3.17  | 0.0939  |
| CD      | 0.63  | 0.4374  |
| A²      | 44.90 | <0.0001 |
| B²      | 20.13 | 0.0004  |
| C²      | 102.71| <0.0001 |
| D²      | 8.02  | 0.0120  |

Sum to say, the effect of dynamic reserves on the production decline rate are the greatest, and the permeability and work schedule are the next; the last one is field pressure. From figures of surface analysis (Figure 3, figure 4), in the case of a certain permeability, decline rate will decrease with dynamic reserves increasing; in the case of a certain dynamic reserves, decline rate will increase with permeability increasing.

![Figure 1. 2D graph of response surface analysis](image)

![Figure 2. 3D graph of response surface analysis](image)

### 3.3 Models

According to the results of the significance analysis, the annual decline rate model can be simplified and established.

For the first year,

\[
R_1 = -0.090551 + 0.094042 \times A + 0.024932 \times B - 0.20879 \times C + 0.042396 \times D - 8.15528 \times 10^{-3} \times A \times C
- 4.96369 \times 10^{-3} \times A^2 - 5.18527 \times 10^{-4} \times B^2 + 0.036151 \times C^2 - 3.63577 \times 10^{-3} \times D^2
\]  

(2)

For the second year,

\[
R_2 = -0.050507 + 0.089606 \times A + 0.021573 \times B - 0.20557 \times C + 0.036962 \times D - 7.56924 \times 10^{-3} \times A \times C
- 4.78208 \times 10^{-3} \times A^2 - 4.50191 \times 10^{-4} \times B^2 + 0.036003 \times C^2 - 3.21836 \times 10^{-3} \times D^2
\]  

(3)

For the third year,

\[
R_3 = 0.09066 + 0.085406A + 0.0177B - 0.21102C - 7.65047 \times 10^{-3} \times AC
- 4.44929 \times 10^{-3} \times A^2 - 3.69869 \times 10^{-4} \times B^2 + 0.038081 \times C^2
\]  

(4)

For the forth year,
\[ R_4 = 0.11869 + 0.0851045 A + 0.015206 B - 0.21399 C - 7.60067 \times 10^{-3} AC - 4.0441 \times 10^{-3} A^2 - 3.19384 \times 10^{-4} B^2 + 0.038998 C^2 \] (5)

The rest of other years can also be drawn in turn.

4. Model reliability verification
Take the first year decline rate as example to verify reliability with numerical analysis method. The figure 3 show that The normal probability distribution of residuals for R1 model is basically in a straight line which indicates high accuracy. In addition, the bulk value and prediction value is better distributed on line Y=X around in the figure 4 also convey that model with high accuracy can be applied directly.

5. Example
Taking the well X2 in the A gas field (in the Changqing area) as an example, predicted vale of model and actual production can be contrasted. Well X2 is typical low permeability gas well with relative long production history. The basic parameters of the gas well are as follows: the reservoir permeability is 0.12mD, the field pressure is 17.47MPa, the dynamic reserve is $1.2 \times 10^8 \text{m}^3$; and the production rate of arrangement(before constant pressure production) is about $4.2 \times 10^4 \text{m}^3$. Using the formula (1) ~ (5), the annual decline rate of the well can be calculated year by year (Figure 5), and the production decline is predicted in the Figure 6.

It can be seen from Figure 6, response surface decline rate prediction and actual production is basically the same, which is mean that the decline model can be accurately predict trend of production decline and decline rate.

6. Conclusions
(1) For low permeability gas reservoir in Changqing gas field, dynamic reserves have the greatest influence on the rate of decline in production, the permeability is the second, and then the working
system, field pressure is the least. In the case of a certain permeability, decline rate will decrease with dynamic reserves increasing; while in the case of a certain dynamic reserves, decline rate will increase with permeability increasing.

(2) Annual decline rate can be predicted by response surface analysis without recognizing decline type. The advantage of the new method is summarized as high accuracy and adaptability for low permeability reservoir.

Nomenclature

\(Q_i\)—production rate per day, 10⁴m³/d; \(D_i\)—decline rate; \(n\)—coefficient for decline type; \(x_1\), \(x_2\), ……\(x_k\)—regression model factors; \(\beta_0\), \(\beta_i\), \(\beta_{ij}\)—regression coefficient; \(\varepsilon\)—outliers; \(F\), \(P\)—dimensionless number of significance test; \(A\)—permeability, mD; \(B\)—field pressure, MPa; \(D\)—working schedule(production rate arrangement), 10⁴m³/d; \(R_i\)—annual decline rate by years.

References

[1] Arps JJ. Analysis of decline curves[M].Petroleum Transaction: AIME, 1945. 228-247.
[2] Fetkovich MJ. Decline curve analysis using type curves[J].Journal of Petroleum
[3] Liu Xiaohua, Zou Chunmei, Jiang Yandong et al. Theory and application of modern production
d ecline analysis[J]. Natural Gas Industry, 2010, 30(5):50-54.
[4] Palacio J C, Blasingame T A. Decline curve analysis using type curves analysis of gas well
production data[J]. SPE25909, 1993.
[5] Fraim M L, Wattenbarger R A. Gas reservoir decline curve analysis using type curves with real
gas pseudo-pressure and normalized time [J] SPEFE, 1987, 18(2): 6711
[6] Long D R, Davis M J. Decline curve analysis using type curve[J]. JPT,1988,40(7):909–912.
[7] Chen Yuanqian. Calculation method of reservoir engineering[M].Beijing: Petroleum Industry
Press, 1990:210-227.
[8] Shaoyong Yu. An Improved Methodology To Obtain the Arps Decline Curve Exponent (b) for
Tight/Stacked Gas Reservoirs[J]. SPE-143907-MS present in North American Unconventional
Gas Conference and Exhibition, 2011, 14-16 June, The Woodlands, Texas, USA.
[9] Zhang Chunyu, Jin Daquan, Liu Gangguo et al. Analysis of production rules if horizontal wells in
low-permeability sandstone gas reservoirs and rational production allocation[J]. Journal of oil
and gas technology, 2014,36(11):223-227.
[10] Wang Tao, Yan Ming, Guo Haibo. Application of response surface regression analysis technique
to numerical simulation[J]. Lithologic Reservoir, 2000,23:451-455.
[11] Annadurai G. Design of optimum response surface experiments for adsorption of direct dye on
chitosan [J]. Bioprocess Engineering, 2000,23:451-455.