International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869 (O) 2454-4698 (P), Volume-5, Issue-2, June 2016

A Novel Method for Quantitative Analysis of Engineering Factors Influencing CBM Production

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Abstract - **The factors influencing CBM production are diversified and complicated, and even linear and nonlinear relations coexist. To solve this problem, the method for quantitative analysis of engineering parameters for CBM production was introduced in this study. According to the engineering conditions in L Block, 20 engineering parameters like drilling fluid density and perforation thickness are sorted out from drilling & completion, fracturing and production operations, among which 13 engineering parameters correlated to production were screened out with grey relational analysis and 3 linear factors were eliminated by Person correlation analysis. A mathematical model was established to evaluate the relationship between the gas production rate and 10 engineering parameters. The evaluation showed that the coefficient of liquid drop speed and amount of fracturing fluid are the highest, with -1.072 and -0.0927 respectively. Combined with the actual development results, two major engineering factors the over-rapid drainage rate and the connection between the fracturing crack and limestone aquifer are figured out. This new method effectively characterized the influence of different field operations and engineering parameters on CBM production.**

***Index Terms*-CBM production; quantitative analysis; engineering parameters**

I. INTRODUCTION

At present, the researching methods for factors influencing CBM mainly focus on statistics and numerical simulation.

Former study showed that coal level and distribution, gas content, permeability, underground water, tectonic setting and the optimum influence configuration of each other are the key factors determining CBM productivity [1]. Abnormal formation pressure was also regarded as the main reason affecting CBM production in some blocks [2]. In particular, the dominant factors controlling the production in blocks with low water cut were believed to be the minimum principal stress and the original permeability, while in blocks with high water cut were the original formation permeability and drainage rate [3]. In other blocks, parameters like tectonic conditions, coal thickness, coal seam buried depth, gas content, permeability and hydrogeological conditions, etc. were the main factors affecting CBM production [4]. Still some scholars thought that underground hydrodynamical field and permeability are the key factors [5]. All the researches above have a great significance on the development of CBM.

So far, the research of main factors in L Block CBM production is still in the stage of qualitative analysis of geological factors. By studying the curvature characteristics of the nose-like structure and its relationship with CBM production, research showed that two sets of orthogonal cracks within the structure provided an effective channel for the storage, drainage and migration for coalbed methane [6]. The intensity of the secondary hydrocarbon generation was also thought to restrict the CBM enrichment in the east margin of the Ordos basin [7]. In addition, abnormal formation pressure in L Block affected the vertical distribution of the formation aquifer [8]. Moreover, two sets of aquifer-the overlying limestone strata of Taiyuan Formation and the overlying sandstone strata of Shanxi Formation coal seam-directly affected the water production in CBM wells [9]. Still the water production level was thought to have a direct relationship with the development degree of formation fracture [10]. The conclusion of these studies varies from different researching aspects.

Actually, geological factors such as formation pressure are uncontrollable and also difficult to measure accurately. Meanwhile, quantitative characterization for geological factors like hydrodynamic conditions and tectonic structures are impractical. Therefore, with non-negligible human disturbance, qualitative or half quantitative analysis methods, always fail to get the accurate statistical regularities. When numerical simulation failed to combine with practical production data closely, there is a gap between conclusion drawn from stimulation and the actual, which cannot meet the engineering requirements.

The following are some former notable studies of how engineering parameters influence CBM production during drilling & completion, fracturing and production operations.

Drilling & completion

Studies by Liu Aiping showed that the most important process during completion was the isolation of the overlying strata of coal seam. The density of cement slurry ranging from 1.20 to 1.60 g/cm^3 and flowback rate ranging from 0.5 to 0.8 m/s are optimum for formation damage control [11]. Huang Huazhou observed that poor cementing quality will cause the deceasing of fracturing incentive effect or reservoir collapse, even no production in a well [12]. Studies conducted by Li Xiangcheng concluded that coal rock has a strong suction capacity for drilling and completion fluids and the adsorption retention is serious, which leads to the low flowback rate of gas and the decrease in coal seam permeability [13]. Other scholars argued that high density drilling fluid and cement slurry, high viscous drilling fluid, and large volume of cement slurry and displacement fluid would easily cause an accumulation of solid medium in reservoir pore and fracture. As a result, permeability reduction occurred and gas in the coal seam was blocked [14].Therefore, the drilling &completion operation influenced CBM production in the following two aspects: formation damage caused by drilling fluids; cementing quality, which will affect subsequent operations and then CBM production.

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Fracturing

Chen Zhenhong et al. observed that the CBM productivity per well in Fanzhuang was controlled by sand amount and other parameters during fracturing [15]. Zhang Yi et al. concluded that the formation damage caused by drilling& completion and hydraulic fracturing affected CBM production [16]. Guo Shengqiang held that the fracturing of the upper and lower sandstone or limestone aquifer was the main factor for high water yield and low gas production in Chengzhuang CBM wells [17]. Gao Bo considered that the fracturing fluid absorbed in coal seam pores and cracks resulted in the permeability decrease of the coal seam, which in the end reduced CBM production [18].

Production

Bustin R M believed that peak production resulted from the optimal production system and the most reasonable pressure level of CBM wells [19]. Zhao Qun et al. maintained that high speed production would cause serious damage to CBM formation near the wellbore in a short time, which hindered the expansion of the formation pressure drop funnel [20]. The peak production, which occurred within 10 days after the gas breakthrough, is less than 1 000 m^3 in over half of the wells in L Block. Afterwards, the production rate dropped sharply, indicating an obvious stress sensitivity of the coal seam. Rao Mengyu et al. thought that intermittent production led to the accumulation of coal dust in near-wellbore zone and then disturbed the normal production of CBM [21]. Cao Lihu et al. found that the migration of coal dust would plug fractures in coal seam [22]. In some areas in L Block, the output of coal dust was so high that wells were closed for many times, which put a great challenge to increase the CBM production.

In the article, engineering parameter set during the operation process mean to imply a plenty of geological information, which are controllable and can be quantitatively characterized accurately. Consequently, the method of quantitative analysis of engineering parameters for CBM production was introduced.

Firstly, engineering factors related to CBM production were sorted out with grey relational analysis from engineering processes of drilling & completion, fracturing and production. Then linear factors with accurate or high correlations were eliminated by correlation analysis. Afterwards, the multivariate model between CBM production and engineering parameters was set up with regression analysis. Under this model, the regression coefficient was regarded as the production affecting factor–the "coupling" result of multiple factors. Hence, how these engineering parameters influence the production were quantitatively evaluated.

II. ENGINEERING PARAMETERS QUANTITATIVE ANALYSIS

A. Statistical result of engineering parameters

According to the operation order and the engineering conditions of L Block, engineering parameters during engineering operations of drilling & completion, fracturing and production were selected.

Engineering parameters during drilling & completion

The CBM development in L Block gives priority to vertical wells, which were completed with casing perforation under the depth from 700 to 900 m. Clean water with density 1.01 ~1.08 g/cm^3 and funnel viscosity 20 ~ 35 s was applied when drilling into the coal seam. Leakage and wellbore collapse occurred seriously during the drilling process. As the coal seam soaked by drilling fluid with a relatively long time, there is a high possibility for severe formation damage.

In line with varied well depth and caliper enlargement rate in L Block, the dosage volume of cement slurry and displacement fluid are from 10 to 20 m^3 and 5 to 15 m^3 respectively. The cementing quality varies from medium to high grade during the second cementation operation. Therefore, cement slurry and displacement fluids may have impacts on CBM production.

According to the CBM development condition in L Block, 7 parameters-completion depth (D) , perforation thickness (h) , drilling fluid density (r) , drilling fluid funnel viscosity (FV) , coal seam soaking time (T_c) , cement slurry volume (V_{cs}) and displacement fluid volume (V_{cd}) - are selected as the engineering parameters during D & C operations.

Engineering parameters during fracturing

Active water fracturing fluid was applied in L Block during the fracturing operation with two sizes of quartz proppant, 0.425 ~ 0.85 mm and 0.85 ~1.18 mm respectively. As the water production rate per well is from 0.2 to 150 m3/d, the possibility was that fracturing cracks may have reached the upper limestone aquifer strata of Taiyuan Formation coal seam or the upper sandstone aquifer strata of Shanxi Formation coal seam. On the basis of specific fracturing operation data, 6 parameters-pad fluid volume (V_{fp}) , carrying fluid volume (V_{fc}) , displacement fluid volume (V_{fd}) , fracturing fluid volume (V_f) , sand ratio (C_s) and displacement volume (Q_d) - are selected as the engineering parameters during fracturing operations.

Engineering parameters during production

Former studies about factors during CBM production operations above showed obvious connections between production parameters. Thus, through the analysis of the relationship between these production parameters and the production volume, problems within the production system can be found.

According to actual production data, 7 parameters during production operations, covering gas breakthrough time (T_b) , gas breakthrough casing pressure (P_b) , annulus dynamic liquid level drop velocity (v_d), water production volume (W_w) , water drainage rate (v_w), shut-in periods (T_s) and shut-in frequency (n), are chose for the analysis.

As discussed above, there are 20 engineering parameters during drilling & completion, fracturing and production operations, but not all of them have a connection with production volume. Special methods are needed to separate those independent engineering parameters related to the final production volume. As a consequence, grey relational analysis and correlation analysis were applied.

B. Engineering parameters screening

Grey Relational Analysis

Grey relational analysis uses the similar or dissimilar degree of development situation between factors to measure the correlation degree between these factors. It reveals the characteristics and degree of dynamic relations between objectives and can quantitatively evaluate the nonlinear correlation degree between two variables. There are 4 major steps to utilize this method.

Define mother sequence, subsequence and their parameters

According to the research purpose, choose the daily gas production volume as the mother sequence $X_0(k)$, and take the 20 engineering parameters like completion depth and perforation thickness of 49 wells as the subsequence $X_i(k)$, where i=1 ~ 20, k=1 ~ 49.

Numerical Value Preprocessing

Implement standardization, regularization, mean value treatment, or other processing methods on the original data of the selected sequence.

Calculate the correlation coefficient between sequences

$$\varepsilon_i(k)=\frac{\Delta_i\min+\rho\Delta_i\max}{\Delta_i(k)+\rho\Delta_i\max}$$

where: $\left|\Delta_i(k)=X_0(k)-X_i(k)\right|$;

$$\Delta_i\min=\min_i[\min_k\Delta_i(k)];$$

$$\Delta_i\max=\max_i[\max_k\Delta_i(k)];$$

$\varepsilon_i(k)$ = correlation coefficient of curve X_i and X_0 at point k
ρ = identification coefficient, generally 0.5
$\Delta_i(k)$ = the absolute value of curve X_i and X_0 at point k
$\Delta_i min$= minimum difference of the absolute value
$\Delta_i max$=maximum difference of the absolute value

Calculate the relational degree between sequences

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\varepsilon_i(k)$$

If γ_i is more than 0.5, the relational degree is high. Medium relational degree ranges from 0.3 to 0.5. Low relational degree is less than 0.3. According to the calculation steps above, the grey relational coefficient between daily gas production volume and 20 engineering parameters can be obtained.

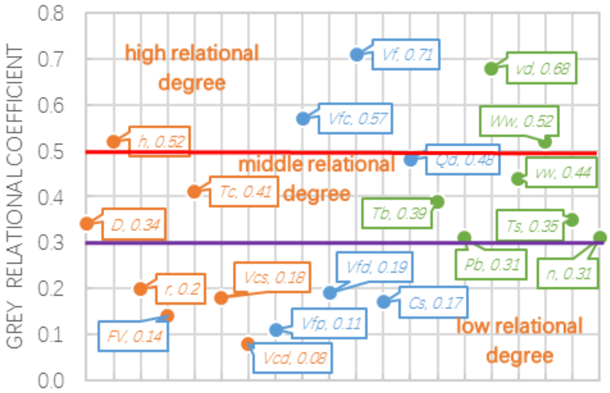

Fig.1 Results of grey relational analysis

From the distribution of the relational coefficient value of each parameter shown in Figure 1, 13 engineering parameters having high relational degree with daily gas production volume are screened out.

Person Correlation Analysis

Among the 13 parameters above, linear relations may exist, with which are called "collinear" factors. These "collinear" factors may cause the distortion of the estimation or inaccuracy in later analysis model. Based on correlation calculation formula, Person correlation analysis is able to quantitatively measure the linear correlation degree between variables. In consequence, Person correlation analysis was applied to remove these "collinear" factors to select independent engineering factors.

$$r=\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2}}$$

Correlation degree is high when *r* is more than 0.8. The *r* of medium relational degree ranges from 0.3 to 0.5, while *r* is less than 0.6 for low relational degree.

The data of 49 wells and 13 engineering parameters are induced in to the correlation coefficient calculation formula. For 13 engineering parameters, correlation analysis are conducted on each pair of them, and parameters with medium to high correlation degree are regarded as "collinear" factors. Parameters with correlation coefficient value over 0.6 are listed in Table 1.

Table 1 Results of correlation analysis

Pamrameters Correlation Coefficient Pamrameters	V_{fc}	V_f	W_w	v_w	T_s	n
V_{fc}	1.00	0.89	0.49	0.44	0.08	-0.14
V_f	0.89	1.00	0.52	0.49	-0.17	0.21
W_w	0.49	0.52	1.00	0.77	-0.33	-0.24
v_w	0.44	0.49	0.77	1.00	-0.30	-0.21
T_s	0.08	-0.17	-0.33	-0.30	1.00	0.68
n	-0.14	0.21	-0.24	-0.21	0.68	1.00

From Table 1, there are 3 pairs of "collinear" factors: fracturing fluid volume and carrying fluid volume, water drainage rate and cumulative water production, shut-in periods and shut-in frequency. Together with Figure1, 3 parameters with high correlation degree, fracturing fluid volume, cumulative water production and shut-in periods, are selected as the influencing factors for CBM production.

Therefore, target engineering parameters are screened out, including completion depth, perforation thickness, soaking time, fracturing fluid volume, fracturing displacement fluid volume, gas breakthrough time, gas breakthrough casing pressure, cumulative water production, annulus dynamic liquid level drop velocity and shut-in periods.

C. Main engineering factors analysis

As the multiple regression analysis is more simple and clear compared to other analysis methods like neural network and support vector machine (SVM), it was chose to model the relationship between production and 10 engineering parameters such as completion depth and fracturing fluid volume. The main engineering factors are screened out by analyzing the coefficient value of each parameter in the standardized regression equations.

Take average daily gas production volume of 49 wells L Block as dependent variables and the 10 selected parameters as independent variables. The following is the multiple regression equation.

$$q = -0.218D + 0.849h - 0.457T_c - 0.927V_f + 0.429Q_d - 0.441T_b$$
$$-0.174P_s - 1.072v_d - 0.776W_w - 0.613T_S + 3.827$$

q = average daily gas production volume, m^3/d
D = completion depth, m
H = perforation thickness, m
T_c = coal seam soaking time, d
V_f = fracturing fluid volume, m^3
Q_d = fracturing displacement fluid volume, m^3/min
T_b = gas breakthrough time, d
P_s = gas breakthrough casing pressure, MPa
v_d = annulus dynamic liquid level drop velocity, m/d
W_w= cumulative water production volume, m^3
T_s = shut-in periods, d

The fitting correlation coefficient of the model is 0.76, showing a high fitting degree. To directly analyze the influence of each parameter on CBM production, with standard regression coefficient of each parameter as y axis and the corresponding parameter as the x axis histogram, influence factors and influence degree distribution, the bar graph of each parameter and their fitting correlation coefficient are listed in Figure 2.

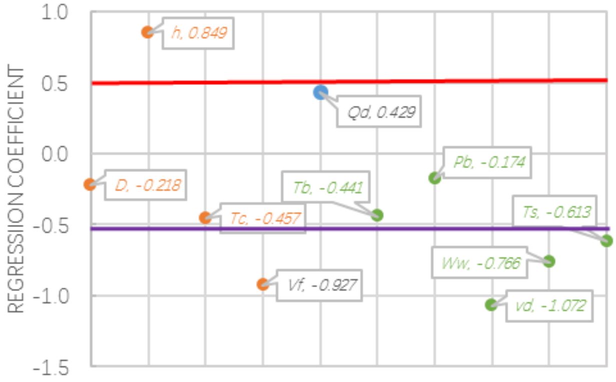

Fig.2 Influence of each parameter on daily CBM production

From Figure 2, some parameters are positively correlated to CBM production, while others are negatively correlated. According to the regression coefficient absolute value, the influence degree of each parameter on CBM production can be sorted out, as shown in the following sequence: annulus dynamic liquid level drop velocity (-1.072) , fracturing fluid volume (-0.927) , perforation thickness (0.849) , cumulative water production (-0.766), shut-in periods (-0.613) , soaking time (-0.457) , fracturing displacement fluid volume (0.429) , gas breakthrough time (-0.441) , completion depth (-0.218) , gas breakthrough casing pressure (-0.174) .

These specific values can be used to analyze the mechanism of each engineering parameter affecting the production through all engineering stages.

Drilling & completion Parameters

Being positively associated CBM production, perforation thickness has the largest influence on CBM production during drilling and completion operations. Perforation thickness to a certain extent represents the thickness of the coal formation. The greater the perforation thickness, the higher the CBM production can be achieved. The next is the coal seam soaking time in drilling fluids, which is negatively associated with CBM production. The longer the coal seam soaking time, the more formation damage will be caused, which leads to lower CBM production. And then completion depth is negatively correlated to CBM production. Completion depth to some degree represents the burial depth of coal seam. The deeper the burial depth, the lower the CBM production will be.

Fracturing Parameters

Fracturing fluid volume is negatively associated with CBM production and has the largest influence on it during fracturing operations. This revealed that fracturing cracks may have reached the limestone aquifer or the sandstone aquifer. The next is fracturing displacement fluid volume, which is negatively associated with CBM production. This indicates that the fracturing displacement fluid volume is so high that fracturing cracks have extended to aquifers. CBM well with low gas production and high water production has long gas breakthrough time and large cumulative water production volume. The negative relation between gas breakthrough time and large cumulative water production volume and CBM production proved the connection between fracturing cracks and aquifers in some well in L Block.

Production Parameters

Being the main controlling factor, annulus dynamic liquid level drop velocity has the largest influence on CBM production during production operations. Annulus dynamic liquid level drop velocity also represents a negative correlation to CBM production, which means that the production rate is too fast in L Block. Then the shut-in periods is also negatively correlated to CBM production, indicating that discontinuous production will lead to lower CBM production in L Block.

Therefore, over-rapid production rate and large scale fracturing are the two main controlling factors for CBM production in L Block. From this perspective, some suggestions come to the corner. The thick coal seam of Shanxi Formation in shallow depth should be developed at first. During the drilling operations, drilling fluids have to prevent collapse as well as leakage with superior ability to control formation damage [23]. The use of fracturing fluid displacement fluid and low carrying fluid should also be controlled [24]. Ensure the extension of cracks in horizontal as much as possible to prevent the connection with aquifers. Further reduce the production rate and guarantee the continuity of production. Intelligent quantitative production technology can also be applied [25]. Meanwhile, it is reasonable to utilize workover fluids that with low formation damage during workovers to prevent the emergence of coal dust [26]. By doing so, high CBM production may be realized.

III. CONCLUSIONS AND DISCUSSION

The study proved that engineering parameters quantitative analysis is able to characterize the influence extent of different engineering operations and parameters on CBM production. The methmatical modeling result is commensurate with the actual CBM development condition in L Block. This is a new method suitable for analyzing the main controlling factors of CBM production.

Through methmatical analysis, over-rapid production rate and large scale fracturing are the two main factors accouting for the unsatisfactory CBM production in L Block. With regards to main controlling factors, high commercial CBM production can be realized by applying formation damage controlling fluids during drilling, completion and workover operations.

Certainly, problems still exist and discussion is necessary.

Only 49 vertical wells are considered in the study. As horizontal well and other well types are now wildly applied in CBM production, more wells and well types need to be included in future study to rule out sample errors.

More engineering parameters should be considered during auntitative analysis. Other parameters that are not analyzed in the study may also have significant effects.

The study only applied 3 methmatical analysis methods. Considering the complexity of factors influencing CBM production, more mathematical methods like factor analysis and cluster analysis should be introduced to form a more comprehensive method to better analyze the factors influencing CBM production.

ACKNOWLEDGMENT

The reseach was supported by National S&T Special Projects (No. 2016ZX05066002-001, Drilling & Completion Technology and Formation Damage Control for CBM, Shale Gas and Tight Gas Multi-Production.

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