High production indexes and the key factors in coalbed methane production: A case in the Hancheng block, southeastern Ordos Basin, China

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\section{1. Introduction}

In recent decades, coalbed methane (CBM) has become an important source of clean energy and a strategic supplement to conventional natural gas (Al-Jubori \textit{et al.}, 2009). As the largest consumer and producer of coal in the world (Dai \textit{et al.}, 2012; Song \textit{et al.}, 2012), China has the third largest CBM reserves, behind those of Russia and Canada (Yun \textit{et al.}, 2012). With the rapid development of CBM industrialization, lower costs and higher gas production per well in CBM commercial development have gradually become important topics in CBM research.

Many researchers have used geological analogy methods or statistical methods to study the production characteristics and factors that influence well production in different CBM basins or blocks. Kaiser \textit{et al.} (1994) conducted a comparison of two CBM basins in the...
United States, the prolific San Juan Basin and the marginally developed Sand Wash Basin, which indicated that the coal distribution and rank, the gas content, the permeability, the ground-water flow, as well as the depositional and structural setting, were critical factors in CBM producibility. Walter and Ayers (2002) reviewed two completely different CBM systems in the San Juan Basin and Powder River Basin and noted that the key parameters to controlling CBM resources and producibility were the thermal maturity, the maceral composition, the gas content, the coal thickness, the fracture density, the in-situ stress, the permeability, the burial history and the hydrologic setting. Scott (2002) proposed that the gas content distribution in coal seams is affected by many hydrogeological factors that could be grouped into the following three categories: the gas generation, coal properties and reservoir conditions. On the basis of previous research results, Su et al. (2005) dissected the interaction of the six geological factors affecting CBM well production in detail as follows: the tectonics and structure, the stratigraphy and sedimentology, the coal rank, the permeability, the gas content and the hydrodynamics. Gentzis et al. (2008) reported the production characteristics of CBM wells in the Fenn Area and Corbett Creek Area in Canada and proposed that the largest effect on gas production volumes is rooted in the application of horizontal drilling technology, especially multi-stage horizontal drilling technology. Through the comprehensive analysis of gas and water variation tendency and the main controlling factors at different production stages based on data from the Panhe Block in the Qinshui Basin, Yang et al. (2008) considered the gas content, the tectonics, the burial depth and the reservoir fracture characteristics to be the important factors affecting CBM production, and high production wells are usually located in fractured area. Sang et al. (2009) analyzed the geological factors that influence production and the production mechanism of CBM wells in the Qinshui Basin, revealing that the coal reservoir structure is the basic factor affecting the productivity of CBM wells whereas the gas content and the permeability are direct geological factors controlling CBM well production. Taking the Fanzhuang Block in the southern part of the Qinshui Basin as an example, Chen et al. (2009) showed that a high production well has a high ratio of the critical desorption pressure to the initial reservoir pressure and vast amounts of sand and fluid are required in CBM fracturing production which could influence the gas production of a single well. In suggesting development proposals, Tao et al. (2012) compared the gas–water production characteristics of 57 CBM wells in the southern Qinshui Basin for 1.5 yr and analyzed the geological and engineering factors that affect the productivity change in the CBM wells in this area. Lv et al. (2012) evaluated the effects of various factors on the temporal and spatial productivity variations and determined that hydraulic fracturing, gas content and permeability, and the structural and hydrogeological conditions have the greatest effect.

Both the geological and engineering factors could affect the productivity of CBM wells. The earlier studies predominantly focused on the basins and areas with a higher level of development, and the production characteristics and key factors in different areas vary greatly. In the Hancheng Block, where the development level is lower and most of the production wells do not reach the desired goal, only a few scholars have analyzed the main control factors of CBM well productivity in recent years. Zeng et al. (2012) found that interlayer interference, production intensity and braise blocking are the most important factors controlling CBM well production in the block based on the pilot production data over 1 yr. Kang et al. (2012) compared and summarized the production characteristics of CBM wells in the Fanzhuang and Hancheng Mining Areas, which are typical high and middle rank coal fields, respectively, and analyzed the effects of perforating thickness, number of perforated layers, unloading technology and stimulation treatment on gas production. Based on the analysis of CBM wells production performance in the Hancheng Block, Shao et al. (2013) built four productivity modes of CBM wells and suggested four aspects of an optimization method for a reasonable production system. However, the influencing factors of CBM

![Fig. 1. Map of the Ordos Basin and the position of the study area.](image-url)
well production in the Hancheng Block are complex, and the key control factors are not clear. The previous research achievements predominantly focused on the analysis of engineering factors instead of geological factors.

The goal of this study is to determine and understand the key factors affecting CBM well production in the Hancheng Block. The correlations between the geological and engineering factors and numerous production data were analyzed comprehensively and systematically using correlation scatter diagrams. The various factors affecting the production performance of CBM wells were determined quantitatively through the grey correlation theory. The results should facilitate establishing a reasonable production system and enhancing CBM recovery.

2. Overview of the Hancheng mining area

The Hancheng Mining Area is in Shanxi province, on the southeastern margin of the Ordos Basin in China, with an area of 1120 km² (Xue et al., 2012). As a result of the regional tectonics, inside the west-dipping monocline, there are numerous small-scale high-angle faults, and most of them could cut through the surface. The Hancheng Mining Area contains an estimated 1.7 × 10¹² m³ of total CBM reserves, and more than 88% of the reserves were buried less than 1000 m deep (Ma and Yin, 2002). The Hancheng Block is located in the southern section of this mining area (Fig. 1).

The main coal-bearing sequences in the mining area occur in the Permian Shanxi Formation and Carboniferous Taiyuan Formation (Fig. 2). The Shanxi Formation is approximately 35–115 m thick and is deposited mainly in a shallow water delta. The main mineable coal seam is the No. 3 seam, which has a general thickness of 1–2 m and a burial depth of 300–1200 m over the entire area. The coal seam structure is simple. The Taiyuan Formation is approximately 26–87 m thick, predominantly deposited in a coastal plain. The No. 5 and No. 11 seams are the main mineable coal seams with complex structures. Among them, the No. 5 coal seam has a general thickness of 1–6 m and a common burial depth of 600–1100 m; in most of the stable distribution area, it parallels the No. 3 coal seam. The No. 11 seam has a general thickness of 2–6 m and a burial depth of 600–1100 m over the entire area, and it is on one side of a wedge (on the other side is the No. 3 coal seam) in the spatial stable distribution area. The injection/falloff well tests demonstrate that most of the coal reservoirs are underpressured and the pressure coefficient is generally 0.6–0.95 (Table 1). According to the tests on the exploration wells, the gas content of these coal seams generally ranges from 6.89 to 13.60 m³/t, and 83% of these coal seams are unsaturated. The coal rank in the mining area ranges from low volatile bituminous to semi-anthracite (Yao et al., 2013).

3. Productivity characteristics of the CBM wells in the Hancheng block

CBM development typically undergoes the following three stages: water drainage and decompression, desorption and gas production and gas production exhaustion (McKee and Bumb, 1987; Schraufnagel, 1993; Xu et al., 2013; Zhao et al., 2014). During
the CBM production process, three corresponding flow regimes typically occur, as follows: single-phase water flow, two-phase gas and water flow and single-phase gas flow (Ates and Barron, 1998; Colmenares and Zoback, 2007; Xu et al., 2014). In this unsaturated CBM field, multi-layer drainage is the major production mode, and most of the production wells in the Hancheng Block must experience a long water drainage stage and unstable gas production stage. Therefore, to analyze the production expediently, the production time of the selected wells is over 2 yr (so far, all the selected wells have produced continuously more than 2 yrs and most of them are concentrated in about 3 yr as well as the longest production time is close to 4 yr), which indicates that the CBM wells have ended the water drainage stage and unstable gas production stage, and entered the continuous and stable gas production stage on the whole and their positions are relatively concentrated.

The average gas and water production column-curves of 36 CBM wells are plotted in Fig. 3, which shows that the average gas production of nine wells is between 1000 and 1500 m³/d, and five wells produce gas at more than 1500 m³/day. The water production on the whole from the CBM reservoir in the block ranges from 1.1 to 27.1 m³ per day.

Table 1
Results of the injection/falloff well tests in the Hancheng Mining Area.

<table>
<thead>
<tr>
<th>Well name</th>
<th>Coal seam</th>
<th>Burial depth (m)</th>
<th>Reservoir pressure (MPa)</th>
<th>Pressure coefficient</th>
<th>Permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 1</td>
<td>3#</td>
<td>345.70</td>
<td>2.80</td>
<td>0.81</td>
<td>1.61</td>
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<tr>
<td>Well 1</td>
<td>5#</td>
<td>375.55</td>
<td>2.39</td>
<td>0.64</td>
<td>2.19</td>
</tr>
<tr>
<td>Well 1</td>
<td>11#</td>
<td>418.85</td>
<td>2.65</td>
<td>0.63</td>
<td>0.20</td>
</tr>
<tr>
<td>Well 2</td>
<td>5#</td>
<td>637.50</td>
<td>5.76</td>
<td>0.90</td>
<td>0.05</td>
</tr>
<tr>
<td>Well 2</td>
<td>11#</td>
<td>672.40</td>
<td>4.12</td>
<td>0.61</td>
<td>0.001</td>
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<tr>
<td>Well 3</td>
<td>11#</td>
<td>1007.00</td>
<td>9.60</td>
<td>0.95</td>
<td>0.02</td>
</tr>
<tr>
<td>Well 4</td>
<td>5#</td>
<td>529.50</td>
<td>4.63</td>
<td>0.87</td>
<td>0.03</td>
</tr>
<tr>
<td>Well 5</td>
<td>3#</td>
<td>1255.50</td>
<td>11.87</td>
<td>0.95</td>
<td>0.37</td>
</tr>
<tr>
<td>Well 5</td>
<td>11#</td>
<td>1323.10</td>
<td>9.22</td>
<td>0.70</td>
<td>0.01</td>
</tr>
<tr>
<td>Well 6</td>
<td>3#</td>
<td>722.10</td>
<td>6.41</td>
<td>0.88</td>
<td>0.35</td>
</tr>
<tr>
<td>Well 6</td>
<td>11#</td>
<td>787.85</td>
<td>6.96</td>
<td>0.88</td>
<td>1.19</td>
</tr>
</tbody>
</table>

4. Effects of the factors on the gas production in the Hancheng block

Many factors could affect CBM development, and the average gas production is the most reliable short-term indicator of the various factors (Ellard et al., 1992; Sparks et al., 1993; Pashin, 1997). Because the key factors are different in different areas, the goal of this study is to determine and understand the key factors affecting CBM well production in the Hancheng Block. The whole research process could be described as follows: (1) investigating the potential influencing factors extensively including the coal rank, the burial depth, the coal thickness, the gas content, the ratio of the critical desorption pressure to the initial reservoir pressure, the permeability/porosity, the ground-water flow, the depositional and structural setting, the fracturing effect, etc. (2) Excluding the parameters which have little influence on the gas production and optimizing the parameters which have larger changes and could be quantized. Here, the previous researches indicated that the coal rank in the Hancheng Block is similar (Yao et al., 2013), the depositional and structural conditions change little (Xue et al., 2012), and the ground-water flow is weak due to the aquicludes between the coal seams and aquifers (Yao et al., 2013), which demonstrated that these factors have little influence on gas production. Thus, the effects from the coal rank, the depositional and structural conditions, and the ground-water flow were excluded. Then, six parameters (the burial depth, the thickness, the gas content, the ratio of the critical desorption pressure to the initial reservoir pressure, the permeability, the fracturing effect) were optimized, which have larger changes and could be quantized. (3) Preliminary analyzing of the correlations between the optimized parameters and numerous production data with the correlation analysis which is suitable for solving the simple inter-relationship between the single factor and variable. (4) Further quantitatively determining the key factors affecting the production performance of CBM wells through the grey correlation theory which is suitable for solving the complex interrelationships between multiple factors and variables. The workflow has been provided in Fig. 4. And this method for the CBM well productivity analysis also could also be applied to other blocks or basins. Moreover, high production indexes were also proposed on the basis of a statistical assessment of the average gas production data from 36 vertical wells in the block.
4.1. Burial depth

In the Hancheng Block, the middle depth of the target coal seams was considered the burial depth, which was used to analyze the correlation of the burial depth and gas production. Fig. 5 shows that the burial depth of the target coal seam ranges from 400 to 770 m based on 36 data points, and the distribution of the high and low production wells is relatively scattered, indicating that there is a poor relationship between the burial depth and daily gas production. Overall, the average gas productivity decreases slightly with the increase of the buried depth; the CBM wells that were perforated in the deep coal seam, which has a depth of more than 700 m, generally produced gas at less than 1500 m³/d. This result indicates that the CBM seepage condition of the shallow coal is better than that of the deep coal because of the better development of the pore-fissure system and the CBM in the shallow coal is easier to be developed because of the easier water fracturing, water drainage and reservoir decompression. Thus, a coal seam with a depth of from 400 to 700 m tends to have a much greater potential for producing CBM.

4.2. Thickness

The coal seam is the prerequisite for CBM accumulation, and a thicker coal seam could result in more gas production because of the richer gas source and the stronger ability to supply gas under the identical conditions in the same area (Pashin, 1991, 1997). Fig. 6 indicates that, with an increase in the perforated coal thickness, the gas production of CBM wells tends to decrease, which is contrary to the above conclusion. This phenomenon contradicts the perception that thick instead of thin coal reservoirs tend to produce very large quantities of CBM. The following reasons could explain this contradiction: (1) the initial reservoir pressure can be depressurized in the thin seams during the initial pumping period; (2) the initial permeability of the CBM reservoir is low and the vertical heterogeneity of permeability in thickness coal seams is remarkable because of the partings and large interlayer spacing in the coal seams (Jin et al., 2004); (3) a fracturing operation might open the sandstone seams close to the coal reservoirs, resulting in the coal seams communicating aquifers. These situations inevitably lead to a limited drainage area, resulting in poor productivity of the thick perforation interval during the initial development period. In the Hancheng Block, 5–11 m is the advantageous thickness for coal seams because the gas production of most wells is more than 1500 m³/d.

4.3. Ratio of the critical desorption pressure to the initial reservoir pressure

In the injection/falloff well test data shown in Table 1, an obvious positive linear relationship between the initial reservoir pressure and the burial depth exists in the Hancheng Mining Area, which could be expressed as

$$p = 0.0088h - 0.4581 \quad (R^2 = 0.8953)$$

where \(h\) is the burial depth of the coal seam, m; and \(p\) is the initial reservoir pressure, MPa.

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The initial reservoir pressure of the coal seam could be computed by Eq. (1), and the result indicates that the initial reservoir pressure in the Hancheng Block varies, with a range of 3–7 MPa. The correlation of the initial reservoir pressure and the gas production is not remarkable. As a whole, greater initial reservoir pressure is associated with lower gas production (Fig. 7).

During production, when successive gas appears in the wellhead as a sign of the initial CBM desorption, the flowing bottom hole pressure at this moment could be regarded as the approximate critical desorption pressure of the CBM reservoir. With the burial depth, the dynamic fluid level and the casing pressure, the critical desorption pressure could be calculated (Tao et al., 2012). Fig. 8 shows that the range of the critical desorption pressure is larger and is from 0.7 to 3.5 MPa, which correlates well with the gas production. With the increase of the critical desorption pressure, the gas production increases obviously, and especially from 1.6 to 3.5 MPa, all of the wells produce CBM at more than 1500 m³ per day.

The ratio of the critical desorption pressure to the initial reservoir pressure is more significant to CBM development. If the ratio is higher, the wells are more economical (Cui and Bustin, 2005; Wang and Ward, 2009). Fig. 9 shows that the ratio lay in the range of 0.1–0.8, on the basis of 36 points, and an obvious positive correlation exists between the ratio and the daily gas production. A coal seam with a critical desorption pressure to initial reservoir pressure ratio of less than 0.3 tends to have less potential for producing CBM (<1000 m³/d). The number of high production wells increases as the ratio increases (>0.3).

4.4. Gas content

In the American evaluation index system for CBM resources and reserves, the gas content represents the CBM productivity (Ross et al., 2009). A low gas content is equivalent to a low gas saturation in the identical structural setting. A small degree of unsaturation could necessitate prolonged dewatering before a large reservoir volume could reach the critical desorption pressure (Price and Ancell, 1993; Pashin, 2010). With the data on the petrophysical properties of the reservoir and the isothermal adsorption experiments, the gas content of the corresponding development wells could be calculated. The gas content of the coal seams in the Hancheng Block is generally lower than that (22–25 m³/t) in the Qinshui Basin coal seams (Lv et al., 2012). The maximum gas content of this block could only reach 12 m³/t. Fig. 10 shows an obvious positive correlation of the gas content and gas production. The gas content of the high productivity coal seam ranges from 6 to 12 m³/t. All the coal seams with a gas content of less than 6 m³/t have low productivity (<1000 m³/t). The reason for this phenomenon is that greater gas content contributes to larger CBM resources in a certain productive section, which ensures good performance in the wells.
4.5. Permeability

Fractures are the main channels for CBM production, and CBM reservoir permeability could reflect the degree of smoothness of the channels (Moore, 2012). The permeability could represent the gas productivity of CBM wells to some degree. Typically, higher permeability is associated with a larger pressure drop funnel extension, which results in larger effective drainage radius and higher gas productivity. According to the injection/falloff well tests, the permeability of the CBM reservoir is generally less than 1 mD (Table 1), which indicates that the coal seam in the Hancheng Block is a typical low-permeability CBM reservoir. The permeability of the producing wells could be predicted by the relationship of the well test permeability and the burial depth. Fig. 11 shows that the relationship between permeability and gas production is a positive correlation. The permeability of the wells, which produce gas at 1500 m$^3$/d, is greater than 0.4 mD.

4.6. Hydraulic fracturing

Because of the low permeability of the coal reservoir, a CBM well could not achieve an adequate production rate unless reservoir stimulation techniques are performed to increase the permeability of the target seam (Wang et al., 2009). Most CBM wells are stimulated by hydraulic fracturing, which is the most widely applied measure to enhance CBM recovery worldwide. Hydraulic fracturing has always been an integral part of the development of CBM fields (Rahman et al., 2007). The total volumes of fracturing fluid and fracturing sand are two important parameters characterizing the fracture scale in the fracturing process. The larger the scale of the hydraulic fracture is, the more fracturing fluid and sand are needed.

During the fracturing process, whether the fracturing sand volume is appropriate directly determines whether the fracturing operation is successful. Generally, a larger fracturing sand volume is more beneficial to increasing the fracture length, width and flow conductivity, which contributes to high gas production. Fig. 12 is the scatter map of the average gas productivity and the fracturing sand volume. It indicates that the fracturing sand volume of the high gas productivity wells (> 1500 m$^3$/d) is more than 28 m$^3$. Seven wells with less than 28 m$^3$ have low productivity (< 1000 m$^3$/d), and one well with more than 37 m$^3$ produces no gas. One immediate explanation of this finding could be that the support fracture conductivity is too low if the fracturing sand volume is not high enough, resulting in an inferior fracturing effect. On the one hand, the proppant particles are crushed under the long-term effects of the in-situ stress, and along with the movement of the fluid, some effective seepage channels are jammed. On the other hand, the non-Darcy flow from the fracturing also could reduce fracture conductivity to a certain extent. If the fracturing sand volume is excessive, the fracturing sand could not enter deep into the ground effectively, revealing that a sand plug always occurs during fracturing, which might stop the pumps because of the excessive pressure.

Enhancing the injection rate of the fracturing fluid by improving the displacement, which increases the inner pressure of a hydraulic fracture, is an important measure to enlarge the width of the fractures and offset the fluid loss in the coal seams. Fig. 13 shows that gas production increases as the cumulative injection increases, revealing that the increase in the cumulative injection broadens the fracture scale, which results in higher productivity of the CBM wells. All of the wells with a gas production of more than 1500 m$^3$/d were treated by injecting more than 350 m$^3$ of fluid during fracturing. The gas production was no more than 1000 m$^3$/day for most of the wells injected with less than 350 m$^3$ of fluid.

However, the volume of fracturing sand and fracturing fluid would be decided by the coal thickness. In order to avoid the effect from coal thickness, the fluid volume and the sand volume per unit thickness are considered some of the better parameters to characterize the fracture

**Fig. 10.** Scatter map of the average gas productivity and the gas content (the area with the average gas rate of more than 1500 m$^3$/d is marked by the star).

**Fig. 11.** Scatter map of the average gas productivity and the permeability (the area with the average gas rate of more than 1500 m$^3$/d is marked by the star).

**Fig. 12.** Scatter map of the average gas productivity and the fracturing sand volume (the area with the average gas rate of more than 1500 m$^3$/d is marked by the star).

**Fig. 13.** Scatter map of the average gas productivity and the fracturing fluid volume (the area with the average gas rate of more than 1500 m$^3$/d is marked by the star).
scale. Figs. 14 and 15 show that both the fracturing sand per meter and the fracturing fluid per meter have an approximate positive correlation with the average gas rate, which is consistent with the fracturing fluid and the fracturing sand (Figs. 12 and 13). However, the correlation coefficients are higher than using fracturing sand and fluid. The volume of fracturing sand and fracturing fluid per meter for the wells, which produce gas at 1500 m$^3$ per day, is greater than 3 m$^3$/m and 40 m$^3$/m, respectively.

Optimization of the fracturing fluid is another important aspect for improving the fracturing effect. In the Hancheng Block, the fracturing fluids mainly can be divided into two types. One is clean fracturing fluid (conventional clean fracturing fluid and dt-1) and the other is active water fracturing fluid (conventional active water fracturing fluid and 1% KCl). The characteristic comparisons of clean fracturing fluid and active water fracturing fluid are described in Table 2 and the laboratory test results of 1% KCl active water fracturing fluid and dt-1 clean fracturing fluid are shown in Table 3.

Although the clean fracturing fluid has stronger sand-carrying ability and fracture-making ability than active water fracturing fluid (Tables 2 and 3), choosing the active water fracturing fluid as the main fracturing fluid is more reasonable from the perspective of cost and reservoir protection, especially 1% KCl which costs only 1/3 of dt-1 clean fracturing fluid and 1/8 of conventional clean fracturing fluid. But even more important, the field application effect shows the enormous difference between them. The gas breakthrough proportion of the 25 wells using 1% KCl as the fracturing fluid is 100%, and 13 wells produce gas at more than 1000 m$^3$ per day. Of five wells with clean fracturing fluid and active water used as the fracturing fluid, three wells produce no gas and two wells produce gas at less than 1000 m$^3$/d. Thus, in the Hancheng Blok, using 1% KCl as the fracturing fluid contributes to high production during fracturing.

5. Grey correlation analysis and the effect of key factors on CBM well productivity

The relationships between CBM well productivity and depth, thickness, ratio of the critical desorption pressure to the initial reservoir pressure, gas content, permeability and effect of hydraulic fracturing have been analyzed. The key factors affecting CBM well productivity should be determined. To determine the predominant factors, grey correlation analysis, which needs to obtain the correlation degrees of all the factors, was introduced to quantify and evaluate the influence of the magnitude of the various factors on CBM well productivity.

5.1. Grey correlation analysis

As an important part of the grey system theory, grey correlation analysis is frequently used to determine whether a close relationship exists between array curves, based on their similarity (Deng, 1989; Kayacan et al., 2010). The purpose of grey correlation analysis is to quantify the correlation degrees of various factors and present the key factors that affect the system development by computing the correlation coefficient and the correlation

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Table 2

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristic</th>
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<tr>
<td></td>
<td>Molecular weight</td>
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<tr>
<td>Clean fracturing fluid</td>
<td>Low</td>
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<tr>
<td>Active water fracturing fluid</td>
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</table>

Table 3

<table>
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<th>Performance index</th>
<th>1% KCI active water fracturing fluid</th>
<th>dt-1 Clean fracturing fluid</th>
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<tr>
<td>Molecular weight</td>
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<td>300–400</td>
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<tr>
<td>Concentration (%)</td>
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<tr>
<td>Viscosity (CP)</td>
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<td>15.0</td>
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<tr>
<td>Sand-carrying ability (s)</td>
<td>2.8</td>
<td>28–35</td>
</tr>
<tr>
<td>Friction (%)</td>
<td>100</td>
<td>30–40</td>
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<tr>
<td>Permeability damage rate basing on five manufactured coal cores (%)</td>
<td>12.53–13.29</td>
<td>15.82–25.01</td>
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</table>

* The test temperature is 18 °C.

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The more similar the curves are, the larger the value of the correlation degree is between the curves, and vice versa. The detailed introduction of grey correlation analysis is stated by section Appendix A.

For the Hancheng Block, the reference array \( \{x(n)k\} \) and comparative arrays \( \{x(n)l\} \) should be established firstly. The reference array consists of the gas production data of all the CBM wells while the comparative arrays are grouped from the various influencing factors derived from the corresponding well sites, including the depth, thickness and other factors. After nondimensionalizing the reference array \( \{x(n)k\} \) and comparative arrays \( \{x(n)l\} \), the correlation coefficient \( r_{nk} \) between the reference array and the comparative arrays in the time of \( n=k \) (point \( k \) on the curves) could be computed by Eq. (A1). Then, the correlation degree \( r_{nk} \) of the comparative arrays to the reference array could be obtained by Eq. (A4) at any time (any point on the curves) at the length of array \( N \) (\( N=36 \)). Finally, the correlation degrees should be ranked. In this case, the values and physical significances of these parameters are presented in Table 4. Here, in order to further illustrate the calculating processes, the burial depth and gas production rate were chosen as an example: (1) the reference array \( \{x(n)k\} \) is the gas production rate and the comparative array \( \{x(n)l\} \) is the burial depth; (2) the reference array \( \{x(n)k\} \) and the comparative array \( \{x(n)l\} \) are nondimensionalized through dividing by the maximum values in the corresponding arrays, respectively; (3) the absolute differences \( \Delta \) between the reference array \( \{x(n)k\} \) and the comparative arrays \( \{x(n)l\} \) and the correlation coefficient \( r_{nk} \) are computed with Eqs. (A2) and (A3) where \( \Delta_{\text{max}} \) is 0.8515; (4) the correlation degree value \( r_{nk} \) (0.5166) is computed by obtaining the average value of all of the correlation coefficients (Table 5).

The result of the above calculations (Table 6) shows that the factors controlling the gas production of the CBM wells are, in decreasing order, the ratio of the critical desorption pressure to the initial reservoir pressure, the volume of fracturing fluid per meter, the gas content, the volume of fracturing sand per meter, the thickness, the permeability and the depth, which suggests that the ratio of the critical desorption pressure to the initial reservoir pressure is the most important factor in determining well productivity, whereas depth is the least important factor.

Compared with the regression analysis, the decreasing order of these correlation degrees from the grey correlation analysis is somewhat different (Table 6), but these results are not contradictory. In the regression analysis, the gas content is on the first place. However, its value in grey correlation analysis is very close to the first factor (ratio of critical desorption pressure to initial reservoir pressure). This fact is in compliance with the physics of phenomena. It should be noticed the very large point’s dispersion (cloud) in all the scatter maps. The regression analysis could preliminarily analyze the factors of CBM well productivity while the grey correlation analysis could further quantitatively determine the key factors on the basis of the internal relations of various factors. The reason for this difference is that the grey correlation analysis is more reliable than the unary linear regression analysis considering the characteristics of these two methods. The unary linear regression analysis only considers whether the relationship between the independent variable (influencing factors) and the dependent variable (gas production rate) could be approximately represented by a straight line, which is easily affected by samples size and their typical distribution (cloud). For example, if a parabolic relation exists between the independent variable and the dependent variable, the unary linear regression is not appropriate and the correlation coefficient is very low. Thus, the actual change law is hard to be found. Moreover, the sample number also has a large effect on the regression analysis. On the contrary, the grey correlation analysis provides a quantitative measure for the changes of system development and is very suitable for dynamic processes and multifactorial analyses. According to the geometry similarity of array curves, whether the various factors are strongly linked could be judged without considering the amount and the distribution of samples. The more similar the curves are, the larger the value of the correlation degree is, and vice versa. The grey correlation analysis not only is particularly applicable to the situation where the statistical information is lacking and the statistical data grey scale is large, but also could reduce the calculation time effectively for the analysis of selected variables.

5.2. Comprehensive analysis of the key factors affecting CBM well productivity

The result of the grey correlation analysis above indicates that both the geological factors and engineering factors are the key factors affecting CBM wells productivity in the Hancheng Block. Among the factors, the three most critical factors are, in decreasing order, the ratio of the critical desorption pressure to the initial reservoir pressure, the volume of fracturing fluid per meter and the gas content. Hydraulic fracturing has always been an integral part of CBM development in the Hancheng Block. In the process of CBM development, the ratio of the critical desorption pressure to the initial reservoir pressure frequently determines the degree of difficulty of the water drainage and decompression in the CBM reservoir. For the Hancheng Block, the ratio with the highest correlation degree (0.7379) and higher fitting degree (0.5411), has the most important effect on gas well productivity, revealing that this block is in the early stage of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Physical significance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>Samples number</td>
<td></td>
</tr>
<tr>
<td>( k(n) )</td>
<td>Reference array, the average gas rate array ranking as the well names H1–H36</td>
<td></td>
</tr>
<tr>
<td>( l(n) )</td>
<td>Comparative arrays, the influencing factors arrays ranking as the well names H1–H36</td>
<td></td>
</tr>
<tr>
<td>( \rho )</td>
<td>Resolution coefficient</td>
<td></td>
</tr>
<tr>
<td>( \Delta_{\text{max}} )</td>
<td>Maximum value of the absolute differences in the arrays</td>
<td></td>
</tr>
<tr>
<td>( \Delta_{\text{min}} )</td>
<td>Minimum of the absolute differences in the arrays</td>
<td></td>
</tr>
<tr>
<td>( x(n)k )</td>
<td>Parameter value on the curves of comparative arrays at the time of ( n=k ) (point ( k ) on the curves)</td>
<td></td>
</tr>
<tr>
<td>( x(n)l )</td>
<td>Parameter value on the curves of reference array at the time of ( n=k )</td>
<td></td>
</tr>
<tr>
<td>( \Delta_{nk} )</td>
<td>Absolute differences between the reference array and the comparative arrays at the time ( n=k )</td>
<td></td>
</tr>
<tr>
<td>( r_{nk} )</td>
<td>Correlation coefficient of the comparative arrays to the reference array at the time of ( n=k )</td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>Length of array, the total number of wells</td>
<td>36</td>
</tr>
<tr>
<td>( s )</td>
<td>Number of the correlation coefficients</td>
<td>1–36</td>
</tr>
</tbody>
</table>

References
development, compared with the development time (2–4 yr). Therefore, the reservoir pressure goes against gas desorption during the water drainage and decompression stage, which is further proved by the relationship between initial reservoir pressure and average gas rate (Fig. 7). If the ratio of the critical desorption pressure to the initial reservoir pressure is higher, which demonstrates that the critical desorption pressure is closer to the initial reservoir pressure and the pressure difference is smaller, CBM is more easily produced.

Generally, gas content is the material basis and permeability is the prerequisite for CBM seepage and production in a reservoir. Gas productivity increases with the increase of permeability and gas content. In addition, a coal seam with a larger thickness contributes to more controlled reserve of CBM wells, which results in stronger gas supply capability and higher gas production. However, in the Hancheng Block, less thickness correlates with greater gas production (Fig. 6), which is contrary to the common sense. Therefore, two parameters, the gas production potential (the thickness \( x \) the gas...
6. Conclusions

1) According to the result of the grey correlation analysis, the factors controlling the gas production of the CBM wells in the Hancheng Block are, in decreasing order, the ratio of the critical desorption pressure to the initial reservoir pressure, the volume of fracturing fluid per meter, the gas content, the volume of fracturing sand per meter, the thickness, the permeability, and the depth. In short, to achieve efficient development of CBM, a comprehensive consideration of coal reservoir geological effects, including the ratio of the critical desorption pressure to the initial reservoir pressure, the gas production potential, and the gas production deliverability, is necessary for optimizing the reservoir. And then, matching the reservoir with perfect hydraulic fracturing construction could further increase the gas well productivity.

2) The ratio of the critical desorption pressure to the initial reservoir pressure frequently determines the difficulty level of the water drainage and decompression of the CBM reservoir. If the ratio is higher, which indicates that the critical desorption pressure is closer to the initial reservoir pressure, the CBM is more easily produced. The gas production potential and deliverability characterize the comprehensive effect of thickness, gas content and permeability on gas productivity. High gas production potential and deliverability are favorable for gas productivity. Hydraulic fracturing has always been an indispensable part in the development of CBM fields.

3) Overall, the Hancheng Block is in the early stage of development. In combination with the gas well production performance, the corresponding parameter indexes of reasonably high production CBM wells were suggested, as follows: the buried depth range should be 400–700 m; the thickness of the coal seam should not be lower than 5 m; the ratio of the critical desorption pressure to the initial reservoir pressure should be greater than 0.3; the gas content should be greater than 6 m3/t; the volume of the fracturing fluid per meter should not be lower than 40 m3/m; the volume of the fracturing sand per meter should not be lower than 3 m3/m; and 1% KCl should be used as the fracturing fluid.

Acknowledgments

This work was financially supported by the Key Project of the National Science & Technology (Grant no. 2011ZX05038-001), the National Natural Science Foundation Project (Grant no. 41272175), the Beijing Higher Education Young Elite Teacher Project and China Postdoctoral Science Foundation funded project (Grant no. 2014M561020). The authors are grateful to anonymous reviewers and the editor Dr. Vural Sander Suicmez for their careful reviews and detailed comments that helped improve the manuscript substantially.

Appendix A. Grey system theory and its application

A.1 Grey system theory and its calculation steps

As an important part of the grey system theory, grey correlation analysis is frequently used to determine whether a close relationship exists between array curves, based on their similarity (Deng, 1982, 1989; Kayacan et al., 2010). The purpose of grey correlation analysis is to understand the things’ feature by quantifying the correlation degrees of various factors and presenting the key factors that affect the system development. According to the geometry similarity of array curves, whether the various factors are strongly linked could be judged without considering the amount and distribution of samples. The grey correlation analysis is not only particularly applicable to the situation where the statistical information is lacking and the statistical data grey scale is large, but also could reduce the calculation time for the analysis of selected variables effectively.

In the process of system development, if the change trends of two factors are almost the same or similar, namely synchronous change degree is high, it could be considered that a large correlation degree exists between the two curves. The more similar the curves are, the larger the value of the correlation degree is, and vice versa. Thus, the grey correlation analysis provides a quantitative measure for the changes of system development and is very suitable for dynamic process analysis.

The application of grey correlation analysis predominantly includes five steps and two computations, which are introduced as follows (Fig. A1):

1) Determining the reference array \( x_0(n) \) and comparative arrays \( x(n) \)

Fig. 16. Scatter map of the average gas productivity and the gas production potential (the area with the average gas rate of more than 1500 m3/d is marked by the star).

Fig. 17. Scatter map of the average gas productivity and the gas production deliverability (the area with the average gas rate of more than 1500 m3/d is marked by the star).
The reference array could reflect the behavior characteristics of the system while the comparative arrays could affect the behavior characteristics of the system.

(2) Non-dimensionalizing the reference array \( \{x_0(n)\} \) and comparative arrays \( \{x_i(n)\} \)

Due to the different physical significances of various factors in the system, the array dimensions are often different, which makes it hard to compare the arrays and obtain the correct conclusion. Therefore, it is necessary to non-dimensionalize the reference array and comparative arrays before the grey correlation analysis is implemented.

(3) Computing the correlation coefficient \( r_{0i}(k) \)

In the grey system theory, the essence of the correlation degree is the geometry difference degree of the array curves. If the reference array \( \{x_0(n)\} \) has a number of comparative arrays \( \{x_i(n)\} \), the correlation coefficient \( r_{0i}(k) \) between the reference array and the comparative arrays at time \( n = k \) (point \( k \) of the curves) could be computed by Eq. (A1):

\[
r_{0i}(k) = \frac{\Delta_{\text{min}} + r \Delta_{\text{max}}}{\Delta_{\text{max}}} \tag{A1}
\]

where \( r \) is the resolution coefficient, \( r > 0 \), and the value is usually 0.5; \( \Delta_{\text{max}} \) and \( \Delta_{\text{min}} \) are the maximum and the minimum value, respectively, of the absolute differences in the arrays; because the comparative arrays are orthogonal after conversion, generally, \( \Delta_{\text{min}} \) is equal to 0. \( \Delta_{00}(k) \) is the absolute difference between the reference array \( \{x_0(n)\} \) and the comparative arrays \( \{x_i(n)\} \) at time \( k \):

\[
\Delta_{00}(k) = |x_0(k) - x_i(k)| \tag{A2}
\]

Thus, the correlation coefficient \( r_{0i}(k) \) could be expressed simply by

\[
r_{0i}(k) = \frac{0.5 \Delta_{\text{max}}}{\Delta_{00}(k) + 0.5 \Delta_{\text{max}}} \tag{A3}
\]

(4) Computing the correlation degree \( r_{0i} \)

Since the correlation coefficient is the absolute difference between the reference array \( \{x_0(n)\} \) and the comparative arrays \( \{x_i(n)\} \) at any time (any point on the curves), the value is non-unique and the information is too dispersive to compare integrally. It is necessary to calculate the average value of all of the correlation coefficients as the expression of the correlation degree of two arrays at each time, and then the correlation degree \( r_{0i} \) is expressed as follows:

\[
r_{0i} = \frac{1}{N} \sum_{i=1}^{N} r_{0i}(S) \tag{A4}
\]

where \( r_{0i} \) is the correlation degree between the reference array \( \{x_0(n)\} \) and the comparative arrays \( \{x_i(n)\} \); \( N \) is the array length; and \( s \) is the number of correlation coefficients.

(5) Ranking the correlation degree \( r_{0i} \)

The close degree of various factors is mainly described by the size order of the correlation degree, except for the size itself. The correlation order \( \{\epsilon_i\} \) is the permutation of comparative arrays \( \{x_i(n)\} \) to the same reference array \( \{x_0(n)\} \), which reflects the advantages and disadvantages of the comparative arrays to the reference array. If \( r_{0i} > r_{0j} \), it could be regarded as array \( \{x_i(n)\} \) is better than array \( \{x_j(n)\} \) to the same reference array \( \{x_0(n)\} \) and denoted by \( [x_i(n)] > [x_j(n)] \).

A.2 Comparison with the traditional regression analysis

The general abstract system often contains many factors that determine the system’s development trend, such as the key factors analysis of the CBM well productivity. Here, we need to determine which factor is the most important and which one comes second. Although the regression analysis in mathematical statistics can be used as a method of abstract system analysis, it has the following drawbacks: (1) the regression analysis requires a large amount of data and the shape of fitting curve is easy to be affected by the number of samples and their distribution. If the data quantity is little, it will be difficult to find out the statistical regularity; (2) the regression analysis requires the samples to obey a typical probability distribution and the relationship is linear between factors and system characteristics data as well as it has nothing to do with each other between various factors. Generally speaking, this requirement can’t be achieved; (3) the calculation quantity of the regression analysis is usually large resulting in that the calculation requires a computer; (4) the quantitative results may not match with the qualitative analysis results which results in the relationship between the system and the regularity to be misrepresented and become upside down; (5) the regression analysis is usually applicable to the simple analysis of a single factor which cannot reflect the intrinsic relationships between independent variables and the dependent variable. When the regression analysis is used to analyze the multifactorial and non-linear case, the error is large; (6) the ultimate goal of the regression analysis is to establish an empirical regression equation and realize the prediction of the dependent variable. But the relationship is diverse and unpredictable and different methods make a great difference in results. Thus, ranking the factors with the goodness of fit from the regression analysis to determine the key factor is unscientific and not accurate. On the contrary, the grey correlation analysis overcomes the shortcomings and the insufficiency of the regression analysis above through analyzing the dynamic process of the system. The method has a small calculation quantity, which is especially suitable for multifactorial and non-linear analysis. Therefore, the result from the grey correlation analysis is more reasonable and accurate.

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