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Research Article

# Multi-well synchronous hydraulic conformance fracturing technology used for deep coal beds and its field application in the Southern Qinshui Basin☆,☆☆

Ye Jianping[a,b], Yang Zhaozhong[c], Xia Rigui[a], Zhang Jian[a] & Li Xiaogang[c,*]

[a] China United Coalbed Methane Co., Ltd., Beijing 100011, China
[b] China National Offshore Oil Corporation, Beijing 100010, China
[c] State Key Laboratory of Oil & Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China

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**Abstract**

For deep CBM productivity improvement, a technical concept of conducting multi-well synchronous hydraulic conformance fracturing was proposed based on its geological characteristics. First, a mathematical model for multi-fracture induced stress was established by using the boundary element displacement discontinuity method, to simulate the distribution of induced stress field in deep coal beds and analyze the possibility of the formation of complex fracture networks induced by the hydraulic conformance fracturing. Then, the propagation situation of fracture networks interfered by stress and its influencing factors were studied by using the discrete element method. And finally, the feasibility of synchronous hydraulic conformance fracturing technology was verified through tri-axial fracturing experiment and field application. It is shown that by virtue of synchronous hydraulic conformance fracturing technology, stress interference area and strength are increased, so horizontal major stress difference is decreased and even the direction of earth stress is changed regionally, which is conducive to the connection of developed face cleats and butt cleats in coal rocks, so as to form large, efficient and complex fracture networks. Furthermore, the favorable conditions for the formation of complex fracture networks by hydraulic conformance fracturing include lower initial horizontal major stress difference, low Poisson's ratio, short well spacing and low fracturing fluid viscosity and high net pressure inside the fractures. Finally, it is shown from the 3D true physical simulation experiments that by virtue of this synchronous hydraulic conformance fracturing technology, natural fractures in coal rocks can be connected sufficiently, and consequently complex fracture networks composed of hydraulic fractures, face cleats and butt cleats are created. Based on these research results, a set of optimization design method for the synchronous hydraulic conformance fracturing of deep coal beds was proposed. Five vertical wells located in the deep coal beds of North Shizhuang Block in the Southern Qinshui Basin were chosen for the pilot test. It is indicated from fracture monitoring and drainage/production data that the stimulated reservoir volume (SRV) of synchronous hydraulic fractured wells is large and its fracture network is complex; and that compared with the conventionally fractured wells, the synchronous hydraulic fractured well is earlier in gas breakthrough, and higher and more stable in production rates and casing pressure and its regional pressure drop even spreads to the adjacent wells, so that their production rates are remarkably raised.
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*Keywords:* Qinshui Basin; Deep coal bed; Coalbed methane; Synchronous fracturing; Stress interference; Fracture network; Discrete element; True tri-axial

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* Corresponding author.
*E-mail address:* 10522300@qq.com (Li X.G.).
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## 1. Introduction

China's coalbed methane (CBM) reservoirs are generally characterized by low pressure, low permeability and low porosity. Basically, hydraulic fracturing is an essential method for each well to reach its economic output [1−8]. In recent years, China's development focus has been gradually shifted from shallow coalbeds to deep coalbeds [9]. The Qinshui Basin is a CBM basin that has been extensively explored and developed in China. Its CBM resources with a burial depth of more than 1000 m account for 47% of the total resources of the whole basin [10−12]. Compared with medium and shallow coal beds, deep coal beds are characterized by "four highs and three lows" (high earth stress, high geothermal gradient, high metamorphic grade and high pore pressure, and low permeability, low porosity and low compressive strength), which makes the fracturing of deep coalbeds more complicated. The hydraulic fracturing technology applicable to medium and shallow coal beds is not applicable to deep coalbeds completely. Therefore, new fracturing technologies and materials must be developed for deep coal beds [13−18]. The porosity and permeability conditions of deep coalbeds are poor, that is, the migration ability of methane in the matrix is poor. In order to obtain an ideal output, it is necessary to "crush" the coal bed needs [13], so as to increase the stimulated reservoir volume (SRV), thus to form a wide range of fracture networks to reduce the seepage resistance and distance in the matrix. Relative to shale reservoirs, the brittleness index of deep coal bed reservoirs [19−21] is still very low, which is unfavorable for the formation of complex fracture networks. The horizontal principal stress difference of deep coal beds is relatively high, so hydraulic fractures can more easily pass through natural fractures directly without being captured by natural fractures, which is also unfavorable for the formation of complex fracture networks. However, a large number of natural fractures such as face and butt cleats are developed in deep coal beds [22,23]. Therefore, connecting the natural fractures effectively is the key to successful fracturing of deep coal beds.

In 2006, synchronous fracturing was first implemented in two approximately parallel horizontal wells in the Barnett shale play in the Fort Worth Basin, the US. After fracturing, both wells obtained a high output [24,25]. Analysis suggests that this result is caused by the stress interference produced by hydraulic fractures of the two wells. Accordingly, the authors proposed using the multi-well synchronous hydraulic conformance fracturing technology in vertical wells of deep coalbeds. Theoretically, the hydraulic fractures between vertical wells of hydraulic conformance fracturing form a "face interference" effect, and its hydraulic conformance range is larger than the interference range between fractures of synchronous fracturing of horizontal wells, and the latter also faces the risk of connection of two wells [26]. While multi-well synchronous hydraulic conformance fracturing can effectively connect the face and butt cleats of reservoirs between wells, and "crush" the coalbed on a large scale, thus effectively increasing the SRV. Previous researches mostly focused on the initiation and propagation of multiple fractures of horizontal wells, with the stress interference of hydraulic fractures considered [27−29], but rarely research the distribution of induced stress of vertical fractures of multiple vertical wells on the horizontal plane, so the stress interference mechanism were not revealed. There are few numerical simulation researches on the fracture propagation of coal rocks at home and abroad, so it is difficult to consider the influence of coal-bed cleats. Moreover, many scholars performed true tri-axial large-scale experiments to study the fracture initiation and propagation rules [30,31], but few considered the concept of multi-well fracturing.

In this paper, the distribution of induced stress field of deep coal beds was simulated based on the boundary element displacement discontinuity method (DDM) to analyze the potential possibility of the formation of complex fracture networks by hydraulic conformance fracturing. The fracture network propagation with stress interference was discussed using discrete element method (DEM) to identify the influence of single factors on the fracture network conformance area. Finally, the formation of complex fracture networks was verified through the true tri-axial fracturing experiment, and the mechanical mechanism of hydraulic conformance fracturing and the feasibility of its application in deep coal beds were revealed according to the field application effects.

## 2. Mechanical mechanism of multi-well synchronous hydraulic conformance fracturing

### 2.1. DDM-based stress interference numerical simulation

#### 2.1.1. Simulation method

The Displacement Discontinuity Method (DDM) [32,33] is one of the indirect boundary element methods, which can accurately calculate the induced stress produced by vertical fractures at any position on the horizontal plane. The shear stress ($\overset{i}{\sigma}_{\mathrm{s}}$) and normal stress ($\overset{i}{\sigma}_{\mathrm{n}}$) of the midpoint of any unit $i$ in hydraulic fractures can be obtained from the displacement discontinuous quantity of unit $j$ through the equation below:

$$\begin{cases} \overset{i}{\sigma}_{\mathrm{s}} = \sum\limits_{j=1}^{N} \overset{i,j}{A}_{\mathrm{ss}} \overset{j}{D}_{\mathrm{s}} + \sum\limits_{j=1}^{N} \overset{i,j}{A}_{\mathrm{sn}} \overset{j}{D}_{\mathrm{n}} \\ \overset{i}{\sigma}_{\mathrm{n}} = \sum\limits_{j=1}^{N} \overset{i,j}{A}_{\mathrm{ns}} \overset{j}{D}_{\mathrm{s}} + \sum\limits_{j=1}^{N} \overset{i,j}{A}_{\mathrm{nn}} \overset{j}{D}_{\mathrm{n}} \end{cases} \quad (1)$$

where, $\overset{i,j}{A}_{\mathrm{ss}}, \overset{i,j}{A}_{\mathrm{sn}}, \overset{i,j}{A}_{\mathrm{ns}}, \overset{i,j}{A}_{\mathrm{nn}}$ represent the boundary stress influencing factors (MPa/m); similarly, $\overset{j}{D}_{\mathrm{s}}$: the tangential displacement discontinuous quantity of unit $j$ (m); and $\overset{j}{D}_{\mathrm{n}}$: the normal displacement discontinuous quantity of unit $j$ (m).

The induced stress produced by the discrete unit of fractures is superposed based on Equation (1), and then the component of induced stress produced at any point of the whole fracture is obtained.

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